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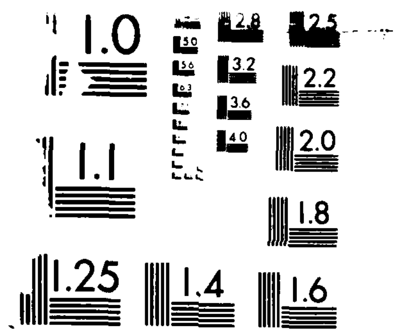

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CRDEC-CR-87009

SUBSTITUTION OF FOG OIL WITH DIESEL FUEL USING A THERMOMECHANICAL APPROACH

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The primary objective of this work was to investigate the possibility of improving the quality (yield and persistence) of diesel fuel as a screening smoke by thermomechanical means such as controlling the degrees of superheat in the diesel fuel vapors and the rates of formation of condensation nuclei via nozzle design and mixing with ambient air.

A smoke tunnel 42 inches in cross-section and 16 feet long was constructed. The obscuring power of the smoke was quantified by measuring light transmitted by a helium-neon laser light source.

Results of the work to date indicate that substantial improvement in the quality of diesel fuel smoke can be achieved by thermomechanical means. Dispersal of a solid such as talc in the diesel smoke also increased obscuration but not dramatically.

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PREFACE

The work described in this report was authorized under Contract No. DAAA15-85-C-0089. This work was started in August 1985 and completed in June 1986.

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SUBSTITUTION OF FOG OIL WITH DIESEL FUEL USING A THERMOMECHANICAL APPROACH

1. INTRODUCTION

The U.S. Army Chemical Research, Development and Engineering Center desires to use diesel fuel in place of fog oil in generating screening smokes for armored vehicles. Diesel fuel is preferred because it is more readily available near the battlefield, is much less expensive and can be vaporized at much lower temperatures. Unfortunately, the diesel fuel produces a satisfactory screening smoke with current generator technology only when the ambient temperature is less than 10°C, whereas fog oil smokes are acceptable even at ambient temperatures as high as 40°C. Furthermore, at ambient temperatures above 25°C diesel fuel smoke dissipates rapidly. In terms of duration times of visual obscuration, a diesel fuel smoke (as observed in field trials) persisted for about five (5) minutes compared to ten (10) minutes for a fog oil smoke.

The principal focus of this research effort for the substitution of fog oil with diesel fuel has been to investigate the possibility of improving the yield and persistence of the smoke produced from diesel fuel by thermomechanical means. The thermal aspect involves the control of the superheat of the diesel fuel and the subsequent condensation by external mixing with air, water, brine or steam and by premixing the diesel fuel with water, brine or steam to provide condensation nuclei and heat transfer sinks. The mechanical aspect is related to the design of the nozzle which is obviously controlled by the thermal aspects.

To accomplish the work effort associated with the thermomechanical approach, a smoke chamber which provides for measuring the obscuring power of the smoke generated from diesel fuel to that generated from fog oil at various ambient temperatures and humidities, superheats, feed rates, feed durations, discharge nozzles and combinations of additives has been designed, erected and tested. Ambient conditions at the time tests were made in the smoke chamber varied from 37 to 78°F and 37 to 78 percent relative humidity. Superheats of the smoke materials have been varied from essentially the saturation point (0°F superheat) to about 270°F. Feed rates have been varied from 14.7 to 37.2 ml/min with feed durations of three (3) to five (5) minutes. Additives which have been investigated include water, 10 percent by weight sodium chloride (NaCl) solution, talc and air with the addition being made either by premixing or post mixing the additive with the diesel fuel. Nozzle designs and configurations used included a standard venturi nozzle (0.125-inch throat), open tube discharge nozzles (0.117-inch and 0.18-inch openings) and a mini-venturi/eductor nozzle.

It should be pointed out that most of the effort in this research program focused on the "leap frog" approach, which was initiated after the Second Diesel Fuel Chemical Conference, January 14 and 15, 1986, to identify significant design and operating parameters rather than to conduct a systematic and detailed evaluation. Since this "leap-frog" approach was used throughout most of the experimental program, only the most significant effects have been identified with any degree of certainty.

2. THEORETICAL BASIS AND BACKGROUND

Although the physics and chemistry of aerosols has been the subject of comprehensive studies by many prominent investigators, a plethora of unanswered questions regarding their behavior still remains. For example, one of the underlying premises has been that a satisfactory screening smoke can be produced from diesel fuel simply by incorporating an additive which reduces the rate of evaporation or mass transfer. However, it is conceivable that a satisfactory smoke can be achieved by altering the conditions for heat transfer or by changing either the operating conditions or the mechanical design of elements in the smoke generator without tampering with the vapor pressure of the diesel fuel. For example, Smirnov in Russia (1948) demonstrated that intensive local cooling (by liquid air) of the vapor of a liquid resulted in a copious formation of fog regardless of the vapor pressure of the liquid. In fact, fogs have been produced by this technique with substances as volatile as pentane which has a normal boiling point of 35°C.

There is little doubt that the most effective way of producing a screening smoke on the battlefield is via the process of vaporization followed by condensation. Although the vaporization step is straight forward and does not affect the quality of the smoke (assuming, of course, that the vaporization is complete, that the liquid does not decompose during the heating to its boiling point or that the resulting vapors do not react in part with the hot exhaust gases from the generator), the condensation step can "make or break" the quality of the aerosol. The objective in condensation is to form, eventually, liquid droplets on the order of one micron which perform the screening or obscuration function. Ideally, all of the vapor should be condensed into droplets since the vapor itself does not have screening capability. Over a period time, these droplets undergo a combination of evaporation and atmospheric dispersion and the smoke eventually dissipates. A complicating aspect of the condensation process is that the initial particles that are formed should be of a critical size (depending on the surface tension, temperature, liquid density and molecular weight; for water the critical diameter is of the order of 0.001 microns). Nuclei above this critical size will continue to grow as liquid droplets; below this size they will evaporate and disappear. Obviously, then, the problem in condensation is to form an adequate number of nuclei which can grow and ultimately condense most of the vapor available. Though much of the recent work has focused on the effect of composition and, particularly, molecular weight on vapor pressure, a simplified but plausible argument suggests its role in nucleation. Molecular collision theory states that the rate of collision depends on relative molecular velocities (speed <u>and</u> direction) among other quantities. When released to a reduced pressure at the same given temperature, a lower molecular weight vapor will seek to occupy a larger volume than one of higher molecular weight. Consequently, molecular velocity components are biased to a greater degree in the radial direction. This more dispersive mode would reduce collision frequency and nucleation. Condensation can only be achieved by cooling the vapors via heat exchange with the local surroundings; considering the fact that heat transfer, condensation of nuclei and initiation of growth have to transpire in a matter of milliseconds, it is apparent that conditions have to be just right.

The magnitude and nature of the problem can be visualized by referring to Figures 1 and 2 which represent the liquid-vapor domes for water and a higher aliphatic hydrocarbon (e.g., the diesel fuel will be approximated by tetradecane, $C_{14}H_{30}$, because the behavior of an n-component diesel fuel would require an n + 1 dimensional representation), respectively. Assume water vapor is formed at 2 atmospheres pressure and 125°C (slightly superheated) and is discharged from a throttling nozzle into the atmosphere. It is convenient to visualize this process in two (2) steps, an isenthalpic expansion from (a) to (b) and a cooling at constant pressure, by heat transfer to the local surroundings (in reality the expansion and cooling occur simultaneously along some irreversible path between (a) and (c) as shown by the dashed line in Figure 1). Similar reasoning applies to the diesel fuel; the major difference to be noted is that its vapor-liquid dome doubles back sharply (retrograde behavior). As can be seen from the diagram of Figure 2, the diesel fuel must be cooled over a much greater distance before it penetrates the two phase dome than the water must. This observation is simply another way of saying that it is more difficult to nucleate the diesel fuel. On the other hand, even though the fog oil probably has a retrograde vapor-liquid dome similar to diesel fuel, it apparently does not suffer from comparable nucleation difficulties when discharged from the current smoke generators for any or all of the following reasons:

1. The smoke generators were designed to discharge fog oil at a temperature slightly greater than its boiling point (870°F); therefore, the fog oil is only slightly superheated. On the other hand, the diesel fuel being discharged under similar conditions would have about 250°F of superheat; thus, the diesel fuel must be cooled over a greater distance than the fog oil.

2. Fog oil must be heated to a significantly higher temperature to vaporize completely (870°F), which means that the initial temperature difference between the fog oil and surrounding air is greater than for diesel fuel at its boiling end point (650°F). On account of this greater driving force, heat transfer rates from the fog oil will be faster and thus the supply of condensation nuclei will be correspondingly greater.

3. Since fog oil evaporates at a higher temperature than diesel fuel, it likewise condenses at a higher temperature. Again because the heat transfer rates are faster, the relative cooling time for fog oil will be less than for diesel fuel.

4. Studies by Oak Ridge in 1983 concluded that as much as 25 to 30 percent of diesel fuel is lost by oxidation as a result of direct contact mixing with the combustion products of the smoke generator. Oxidation losses of the fog oil may not be so great as that of the diesel fuel.

One could draw the conclusion from this comparison that a premix of vapors of diesel fuel and a small amount of water (e.g., drinking water already available in the field) might be effective in that water tends to form condensation nuclei more readily. It was demonstrated by Dr. Sliepcevich in 1950 that a very dense aerosol of particles in the range of one to two microns (near optimum for screening of visible light) can be produced by vaporizing an

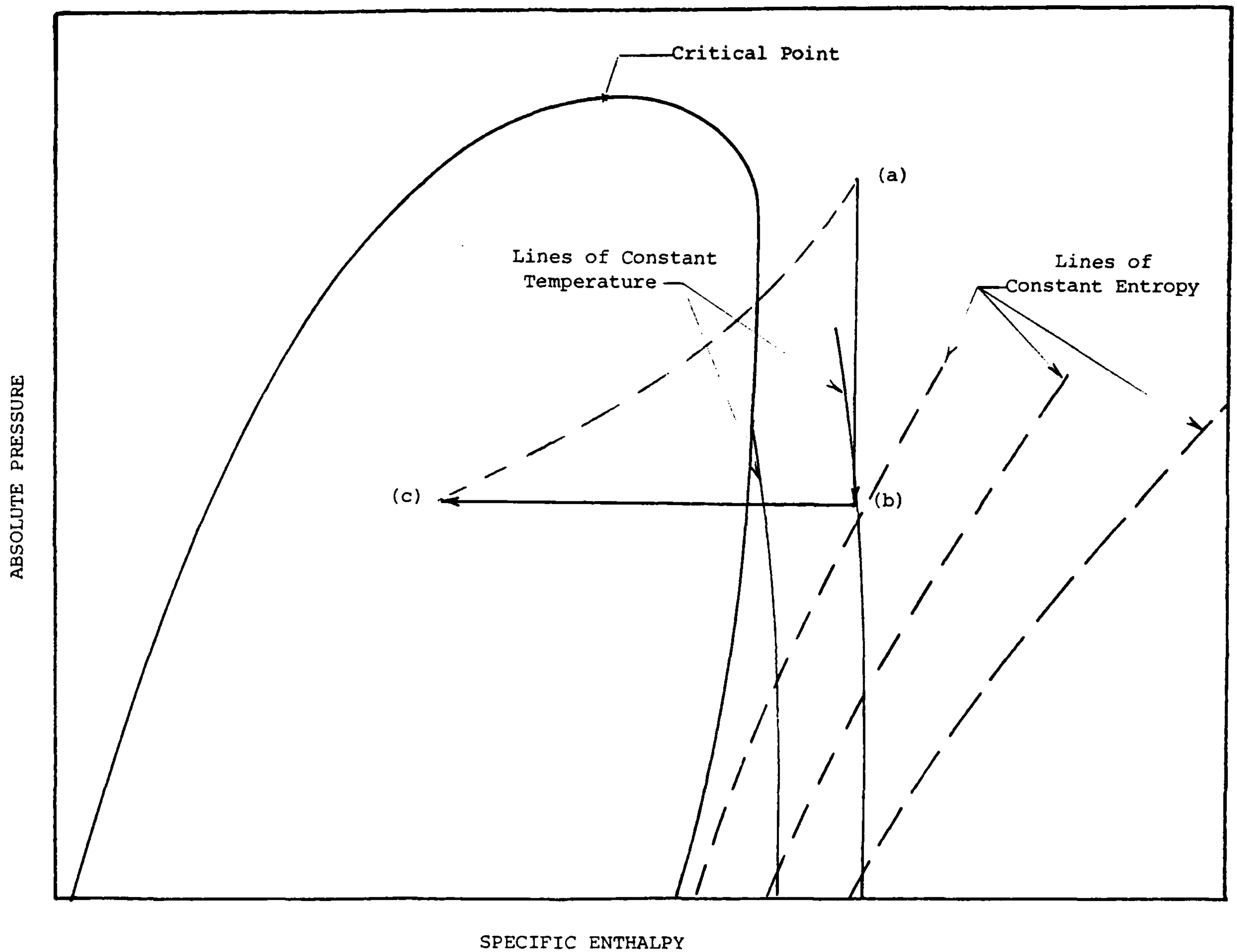

Figure 1. Pressure-Enthalpy Diagram for Water

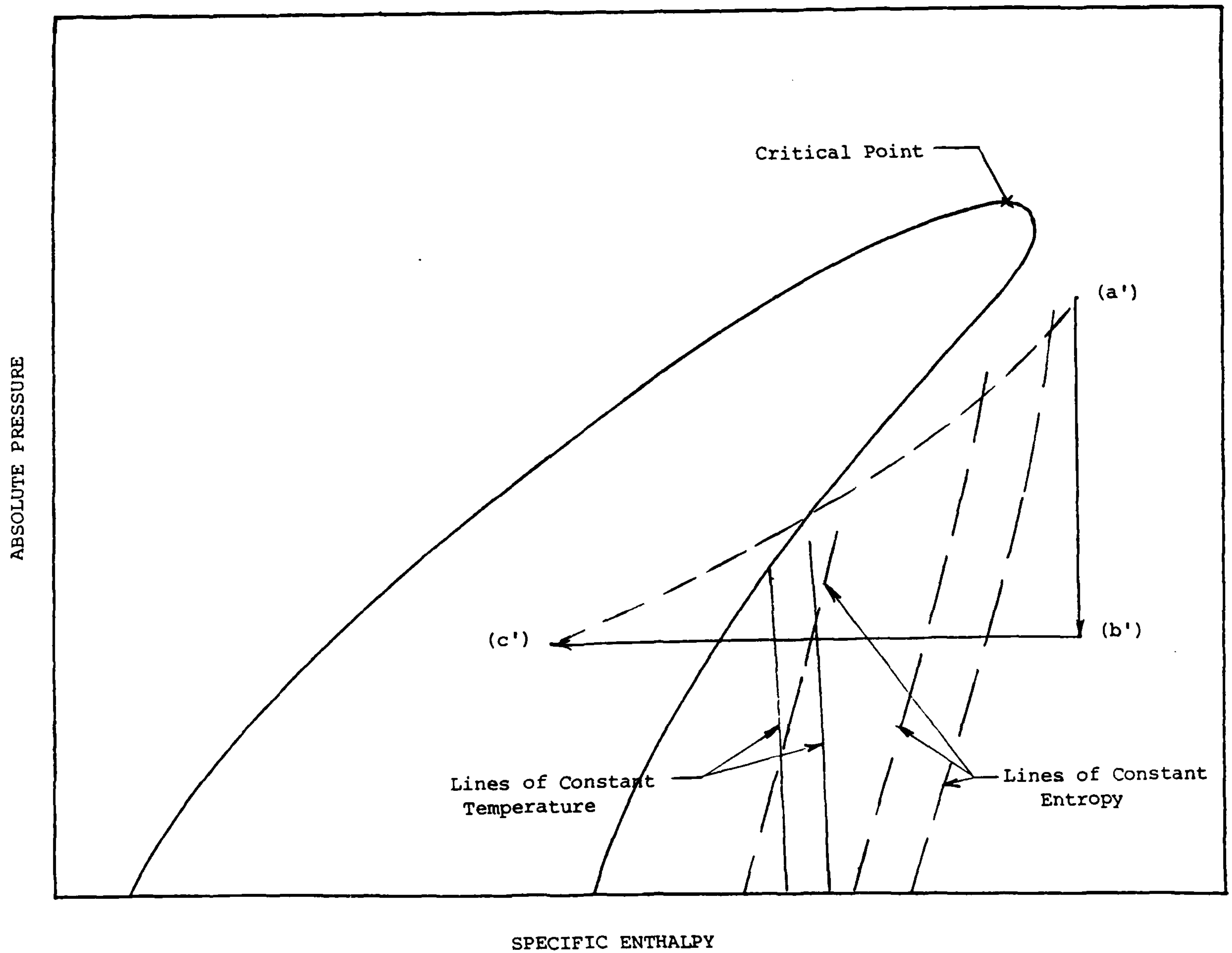

Figure 2. Pressure-Enthalpy Diagram for Tetradecane to Represent Retrograde Behavior of Diesel Fuel

oil-water mixture (about 4 parts oil to one part water) in a coil of tubing that was externally heated. The end of the coil was simply crimped slightly to maintain a back pressure of about one atmosphere gage. It was also demonstrated that by varying the oil/water ratios and the operating temperature, it was possible to produce a "blue smoke" which indicated a preponderance of particles in the quarter-micron range.

It is evident from the diagrams in Figures 1 and 2 that in order to reduce the heat transfer burden during condensation, the vapors should be superheated to a minimal degree.

Another possibility is to combine the diesel fuel vapors (without water) with a spray (atomized) of brine (formed in the field from drinking water plus a small amount of salt) in a diffuser nozzle before discharging into the surroundings. The brine droplets in evaporating will cool the diesel fuel vapors rapidly. When the brine droplets evaporate they will leave suspended tiny particles of salt which can serve as condensation nuclei. It is known that an atomized brine spray by itself produces a reasonable screening smoke as demonstrated by Sliepcevich and co-workers in 1942 during a project on the mechanical formation of screening smokes for the National Defense Research Committee. The effectiveness of the smoke was in part due to the evaporation of water from the droplet, leaving a particle of salt on the order of a few microns suspended in the air.

The foregoing examples are cited to illustrate the types of relatively simple and inexpensive modifications in the operating procedure for the smoke generator that can conceivably result in improved screening smokes from diesel fuel with or without any "magic pill." In particular, these examples illustrate possible approaches which can be used to control the superheat of the diesel fuel.

3. EXPERIMENTAL EQUIPMENT

3.1 Design Considerations.

The overall design considerations for the equipment to be used in this research effort depended on the selection of the size and configuration of the smoke chamber to be installed in the existing low speed wind tunnel available at the University of Oklahoma. After considering fabrication techniques, installation problems in the wind tunnel, wall effects and pressure losses within the smoke chamber and its exhaust stack, a smoke chamber which was 42 in by 42 in by 16 ft in length was selected for this research effort.

Studies by other investigators on clouds and aerosols have indicated that a smoke density of 10^6 particles/cm^3 with each particle having a radius of about one micron is required to produce a suitable smoke for obscuration. Based on this smoke density and particle size, the quantity of liquid required to produce a suitable screening smoke in the selected smoke chamber can be calculated.

$$\text{Liquid Volume} = (\text{Smoke Density})\ (\text{Particle Volume})\ (\text{Chamber Volume})$$

$$= \left(\frac{10^6\ \text{particles}}{\text{cm}^3}\right) \left(\frac{4\pi[0.0001]^3\text{cm}^3}{3\quad \text{particle}}\right) \left(5{,}550{,}720\ \text{cm}^3\right)$$

$$= 23.25\ \text{cm}^3 \text{ of liquid}$$

Since the exact conditions required to produce particles having a radius of one micron are not known with any degree of certainty, design requirements for the equipment must be adequate to provide sufficient latitude in the operating variables to cover a wide range of conditions. After considering the many possible variations to control the superheat of the diesel fuel, candidate additives to improve the smoke quality and operating variables, it was decided that the experimental system should be capable of handling at least 250 cm^3/min of smoke material. Furthermore, since the results obtained from producing smoke from diesel fuel under a variety of conditions are to be compared with those obtained from fog oil, the vaporizer must be capable of generating vapors of fog oil and diesel fuel having a temperature of at least 950°F.

3.2 Description of Experimental Equipment.

The experimental equipment consisted of a feed system of three tanks, pressurizing system, flow meters and tubing; evaporator; discharge nozzle; smoke chamber; light transmission measuring systems; and ancillary equipment of recorders, thermocouples, exhaust fans, internal fans, a heating tape with variable transformer, and a relative humidity and temperature indicator. A flow diagram of the system is presented in Figure 3.

3.2.1 Feed System.

The feed system, as shown in Figure 3, had three feed tanks, a pressurizing system using a high pressure nitrogen source and reducing pressure regulator, flow meters, a feed system to add solids, and tubing. One of the feed tanks was used for diesel fuel, one for fog oil and one for candidate additives to enhance the smoke quality produced from a modified diesel fuel. The feed tank for the diesel fuel was fabricated from 2-inch pipe. This tank was fitted with a sight glass, fill nozzle, pressurizing nitrogen nozzle and outlet nozzle. The feed tanks for the fog oil and candidate additives such as water and brine were fabricated from 1¼-inch PVC pipe. Each was fitted with a sight glass, fill nozzle, pressurizing nitrogen nozzle and outlet nozzle.

The nitrogen source was high pressure nitrogen contained in a conventional cylinder. The desired pressure for the feed tanks was obtained by setting the pressure on the diaphragm valve regulator fitted to the cylinder.

Flow meters used to measure the feed rates of the diesel fuel, fog oil and additive such as water or brine were of the variable area type suitable for panel mounting. The reported capacities of the flow meters based on water flow were 81, 212 and 540 ml/min.

The feed system for the addition of solids to the vapors of the smoke material at the discharge nozzle consisted of a low pressure nitrogen source, a

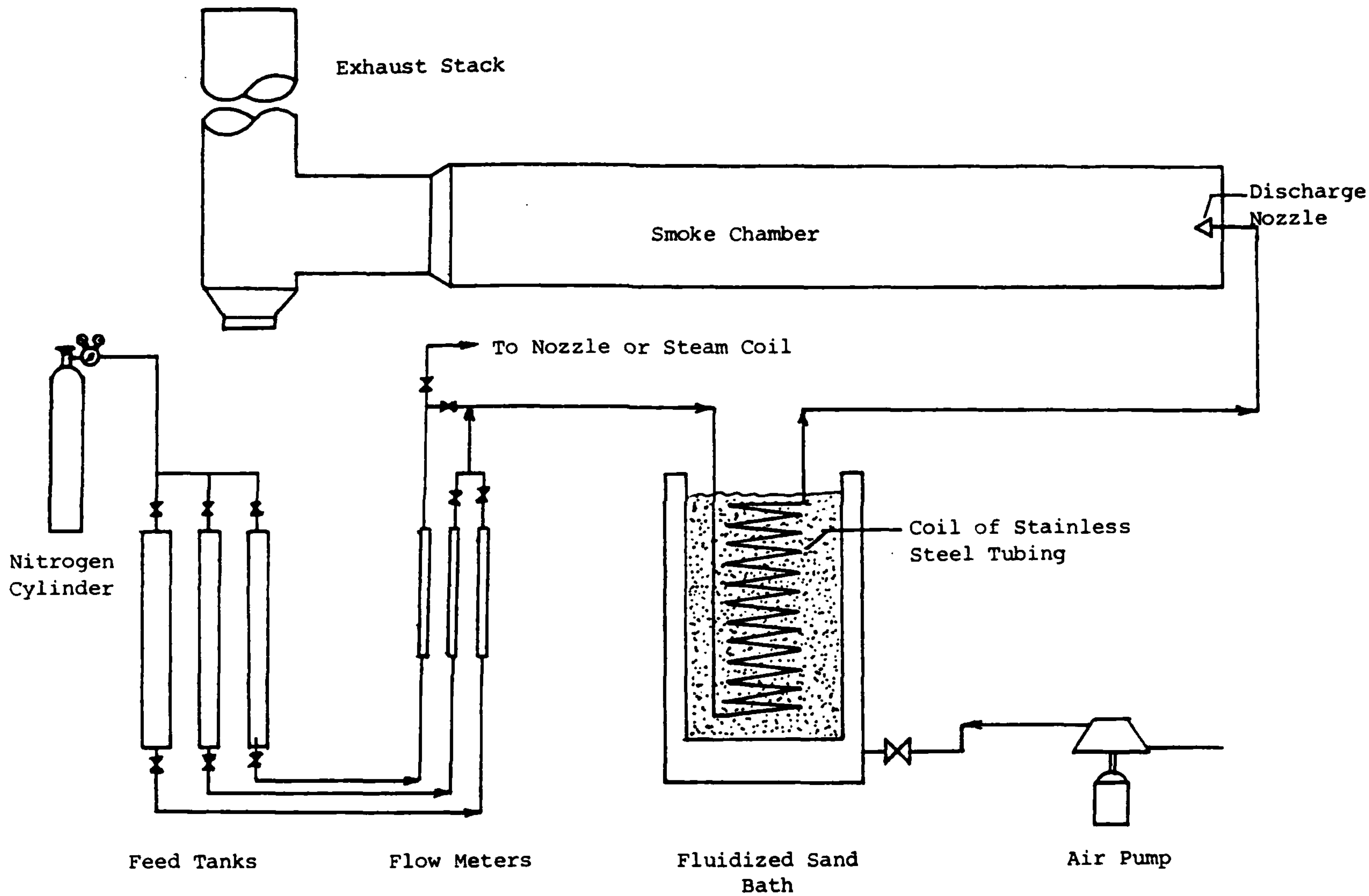

Figure 3. Flow Diagram of Experimental Equipment

container for the solid to be added, a fluidizing tube and copper tubing. The low pressure nitrogen was obtained from the downstream side of the pressure regulator on the nitrogen for the feed system. The container for the solids was a round-bottomed cylinder having an outside diameter of about 1½ in and an overall length of 8 in. The fluidizing tube was made from 1/4-inch copper tubing which extended to the bottom of the solids container. Slots were provided in the end of the tubing to aid in the distribution of nitrogen for fluidization of solids.

3.2.2 Evaporator.

The evaporator consisted of a fluidized sand bath provided with electrical resistance heaters, basic temperature control system and an air pump and a coil of stainless steel tubing (3/16-inch OD by 0.035-inch wall by 40 ft in length) immersed in the sand bath. The fuidized sand bath was manufactured by Techne Incorporated. The air pump suitable for supplying the air necessary to fluidize the sand bath was manufactured by Gast Manufacturing Corporation.

The fluidized sand bath was capable of maintaining an operating temperature of 1112°F (600°C) with an energy input of 4 kilowatts. Four (4), 1,000 watt electrical resistance heaters were located in the base of the sand bath to provide the necessary energy input from a 220 volt electrical supply. Three (3) of the electrical heaters were controlled by on-off switches with the fourth heater provided with an energy control switch which provided a timed on-off function. Considering the energy requirements to vaporize and superheat either the diesel fuel or fog oil at the maximum design rates of about 250 ml/min to a temperature of about 950°F, the capacity of the fluidized sand bath would be extended to its limit of 4 kilowatts.

The evaporator coil of 3/16-inch stainless steel tubing was fabricated from two (2), 20-foot sections of tubing which were joined by a Swagelok coupling. This 40-foot length of tubing was coiled around a standard 4-inch schedule 40 pipe to give an inside diameter for the coil of 4½ in. The overall length of the coil was approximately 12 in when supported on the framework required to suspend the coil in the sand bath. Heat transfer analysis based on preliminary tests conducted in the early phases of the research indicated that the required heat transfer surface area should be at least 0.55 ft^2 for the feed rates being studied. Based on an overall heat transfer coefficient of 10 Btu/hr ft^2°F as calculated from preliminary tests and a log mean temperature difference of 400°F, the coil of 3/16-inch tubing should be at least 36 ft in length. Thus, the 40 ft of tubing used for the coil should be sufficient to provide the necessary heat transfer to vaporize and superheat either the diesel fuel or fog oil to about 950°F.

The inlet and outlet of the coil were provided with connections for the installation of Type J thermocouples directly into the process flow stream. These thermocouples were connected to a 24-point temperature recorder.

The outlet from the vaporizing coil was connected to approximately seven (7) ft of 3/16-inch stainless steel tubing to feed the vapors to the discharge nozzle located at one end of the smoke chamber. In order to minimize

the heat losses from this discharge line, an electrical heating tape (942 watts) using the output from a 240 volt powerstat and fiberglass insulation were wrapped around the discharge line. An additional thermocouple probe (Type J) was installed on the tubing beneath the heating tape and insulation to monitor the temperature of the discharge line.

3.2.3 Discharge Nozzles.

Several basic types of discharge nozzles have been examined in this research effort. These included a standard venturi nozzle, open tube nozzles and a mini-venturi/eductor nozzle.

The first nozzle studied was a standard design for a venturi nozzle, as shown in Figure 4. The converging section of the nozzle was 5/32 in in length with a 30^o angle. The throat was 1/8 in in length with a diameter of 0.125 in. The diverging section of the nozzle had a length of 1 in with an angle of about 5.75 degrees. These dimensions were all within the limits specified for standard venturi nozzles.

Two open tube nozzles were used in this research effort. Each nozzle was made from standard stainless steel tubing which corresponded to the specific size of tubing being used for the discharge line from the vaporizer. One open tube nozzle was a 3/16-inch tube with an opening of 0.118 in; the other open tube nozzle was a 1/4-inch tube with an opening of 0.18 in.

The fourth nozzle used in these studies was a commercially available mini-venturi/eductor manufactured by Fox Valve Development Corporation. This nozzle had a throat diameter of 0.060 in with an eductor port corresponding to 1/8-inch pipe. Figure 5 presents a schematic diagram of the mini-venturi/eductor.

3.2.4 Smoke Chamber.

The smoke chamber with its exhaust stack was made from 22-gage galvanized steel. The smoke chamber was fabricated in four (4) sections, each section being 42 in by 42 in cross-section and 48 in in length. Each section was fitted with observation windows measuring 12 in by 24 in so that qualitative visual assessment of the smoke quality could be made. Schematic diagrams of the smoke chamber and exhaust stack are presented in Figures 6 and 7.

The smoke chamber was provided with two (2) variable speed fans, numbered targets for visual observation of smoke quality and a monochromatic laser light (632 nm) transmittance system for evaluation of smoke quality. The variable speed motors for the fans were mounted external to the smoke chamber with only the shafts extending through the walls of the smoke chamber. These motor shafts were located 21 in from the floor of the smoke chamber approximately 58 in from the discharge nozzle.

Six (6) sequentially numbered targets, each 3 in by 4½ in with a white numeral on a black background, were mounted in the smoke chamber approximately 70 in from the discharge nozzle. These targets were positioned

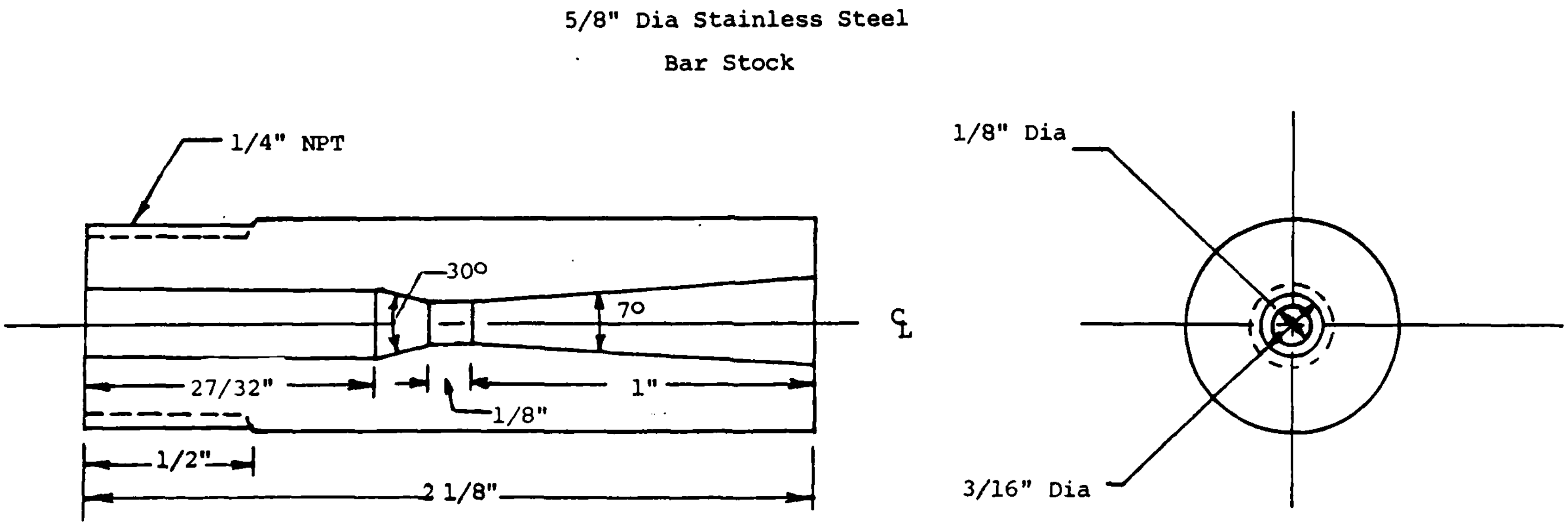

Figure 4. Schematic Diagram of Venturi Discharge Nozzle

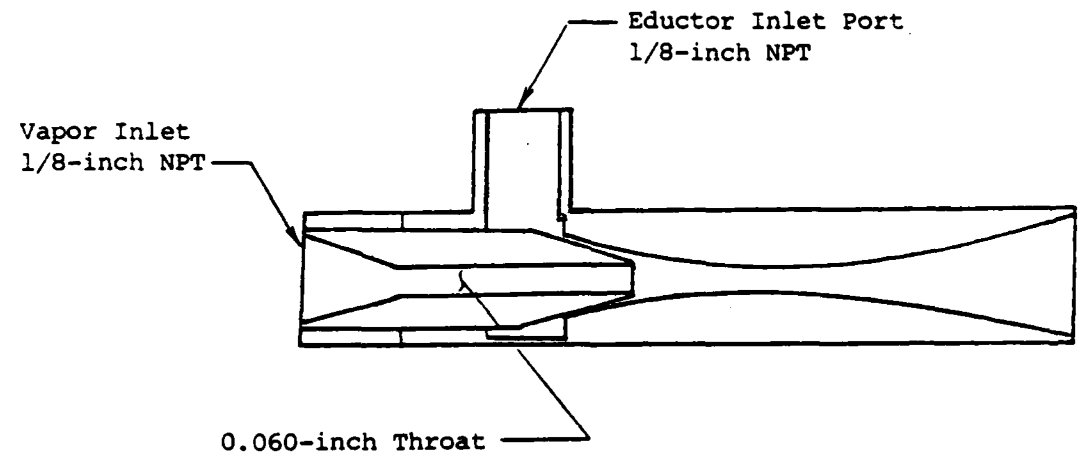

Figure 5. Schematic Diagram of Mini-Venturi/Eductor

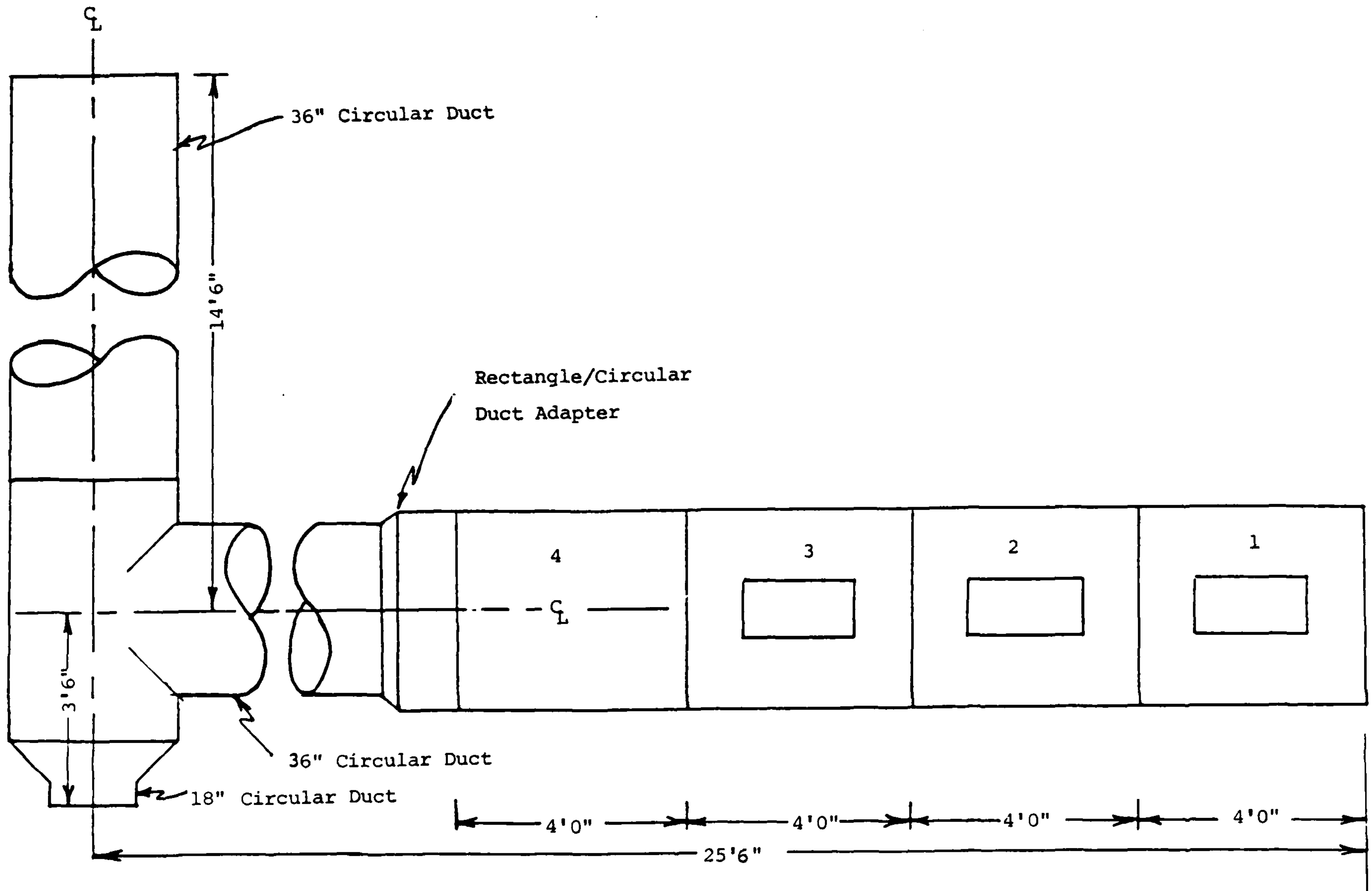

Figure 6. Schematic Diagram of Smoke Chamber and Exhaust Stack

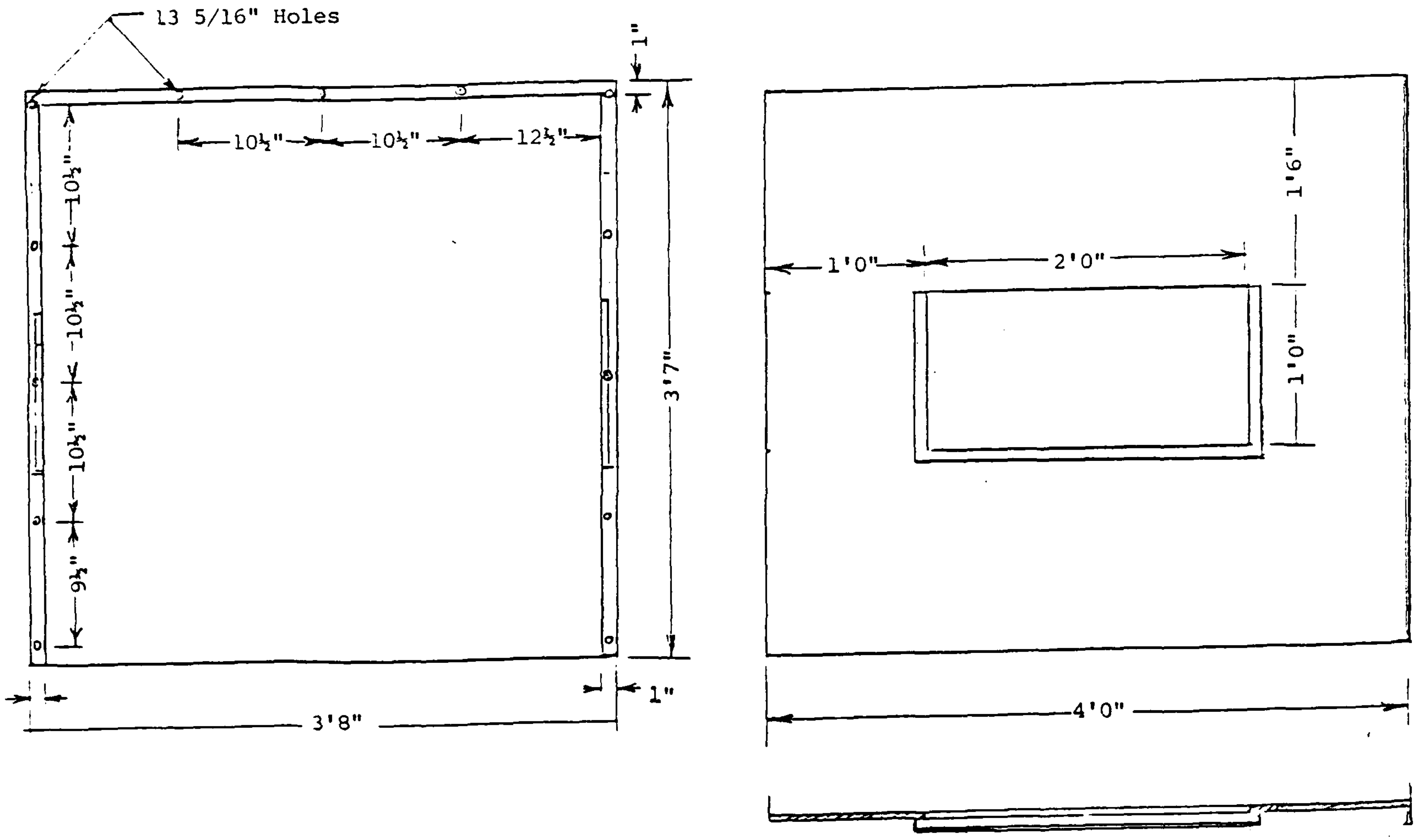

Figure 7. Schematic Diagram of Smoke Chamber Section

at six-inch intervals across the smoke chamber in such a manner that each was visible through the observation window provided in the second section of the smoke chamber.

One laser light transmission measuring system, which was mounted on an optical bench, was positioned inside the smoke chamber at a distance of about 8 ft from the fog source. Adjustment of the optical bench height provided a light beam from the helium-neon laser which was 21 in from the floor of the smoke chamber or essentially at the middle of the smoke chamber.

The exhaust stack of the system was also constructed from 22-gage galvanized steel sections with each section being 3 ft in length. The first section was a transition piece which changed the square cross section of the smoke chamber to a circular cross section having a diameter of 36 in. The horizontal circular duct extended approximately 8 ft where it was joined to a tee. The downward portion of the tee was reduced in cross section from 36 to 18 in. The open end of this reducer was approximately 18 in from the floor. The upward portion of the tee was extended to a height of about 14 ft from the floor of the wind tunnel so that the top of the stack would be near an exhaust fan provided in the louvered portion of the wind tunnel.

Toward the end of this phase of the project, an additional light transmittance system was located inside the exhaust stack near the top. The optical bench was installed so that the smoke traversing the stack would pass through the light beam from the helium-neon laser without interference from any framework or supports for the system.

3.2.5 Light Transmission Measuring System.

Each light transmission measuring system consisted of a helium-neon laser (light source), at least one laser power meter (light receiver) and an optical bench to provide proper alignment of the laser and one or more laser power meters. The helium-neon lasers, Model No. 155A manufactured by Spectra-Physics, had power outputs varying between 0.4 and 0.76 milliwatts. The wavelength of the laser was 632.8 nm which is visible red. These lasers, operating from 115 VAC at 50/60 Hz power source, exhibited a minimum of amplitude noise and ripple and a long-term power drift of 2.5 percent.

The laser power meters, Model No. 45-230 manufactured by Metrologic Instruments, Inc., were photometers powered by two 9-volt transistor batteries. The detector for each meter was a silicon photosensor with a one square centimeter active area. An eight-position switch enabled full scale measurements from 0.003 to 10 milliwatts. Output terminals provided an analog signal which was used as the input to a strip chart recorder.

The optical bench for the mounting of the laser and photosensors used in the smoke chamber was constructed from a rigid framework provided with leveling legs and four (4) adjustable vertical rods which supported three (3) horizontal tracks. The laser and photosensors were supported by these tracks. With the four (4) adjustable supports, proper alignment of the laser beam and photosensors could be made conveniently to obtain a maximum reading from the photosensors. The tracks also facilitated realignment of the system should the distance between the laser and photosensors need to be changed.

The optical bench for the mounting of the laser and photosensor used in the exhaust stack was suspended from a concrete beam located near the exhaust stack since the thin metal of the stack did not provide a rigid support for the optical bench. A rigid framework of channel iron which could be supported by the concrete beam, yet not interfere with the traversing of the smoke through the light beam, was fabricated. Two metal tracks were suspended from this metal framework by four (4) adjustable vertical rods. These tracks were used to support the helium-neon laser. The photosensor was rigidly attached to a 2-inch channel iron support suspended from the base framework. Alignment of the light beam and photosensor was accomplished by adjustment of the four (4) support rods for the two metal tracks supporting the laser.

3.2.6 Ancillary Equipment.

Ancillary equipment required to complete the experimental setup included recorders, thermocouple probes, exhaust fans, internal fans, heating tapes, and relative humidity and temperature indicators.

Two temperature recorders and two strip chart recorders were used in this research program. An 8-point Micromax temperature recorder manufactured by Leeds & Northrup Company was used to monitor the temperature of the fluidized sand bath. This recorder, which used Type K thermocouples (Chromel-Alumel), had a temperature range of 0 to 1200°F (649°C) and a cycle time of about eight (8) minutes for the eight points. The input terminal for the signals from eight different thermocouples was wired so that the signal from a single thermocouple would be printed by each of the eight individual points.

A 24-point Honeywell temperature recorder was used to measure the operating temperatures which included the outlet temperature of the smoke material from the vaporizer, the temperature of the vapor at the entrance to the discharge nozzle, and the temperature of the heated and insulated discharge line between the vaporizer and the discharge nozzle. This recorder was also internally wired on the input terminal board so that only the desired number of temperatures were printed by the 24 points. Type J thermocouples (Iron-Constantan) were used with this recorder.

Two, two-channel strip chart recorders were used to record the outputs from the three laser power meters used in the light transmission measuring systems. These OmniScribe strip chart recorders, manufactured by Houston Instrument, provided five ranges for the input signal per channel and six chart speeds.

The thermocouple probes used in this experimental equipment were grounded thermocouples encased in 0.0625-inch stainless steel sheaths. Both Type J (Iron-Constantan) and Type K (Chromel-Alumel) thermocouple probes were used. The length of the stainless steel sheath was six (6) in.

Two (2) exhaust fans, which were mounted in the louvered portion of the static room of the wind tunnel, were used to provide the necessary draft in the exhaust stack to create a very low wind velocity in the smoke chamber, and to clear the wind tunnel and smoke chamber at the conclusion of a test run.

These belt-driven exhaust fans were provided with 36-inch, four-bladed fans which were supported by two (2) pillow blocks. Switches were provided in the observation room to control operation of the fans. One of the fans was located near the top opening of the exhaust stack.

As previously mentioned in the discussion of the smoke chamber, two variable speed fans were installed in the smoke chamber to provide a uniform distribution in the smoke chamber if it were required and to assist in clearing the smoke chamber at the conclusion of a test run. Twelve-inch, three-bladed fans were provided for these functions. The speed of the motor could be manually adjusted using quick disconnects at the motor to provide four (4) different speeds for the fans. A switch for each motor was provided in the observation room to control operation of the fans.

In order to control the heat loss from the discharge line between the vaporizer and the discharge nozzle, this line was wrapped with an electrical heating tape which could withstand the high temperatures of about 950°F. This 942-watt heating tape had a temperature rating of 1200°F (649°C). Energy input to the tape was controlled by a powerstat which could vary the voltage to the tape from 0 to 240 volts.

A relative humidity and temperature indicator was installed in the test section of the wind tunnel to monitor the ambient conditions. Relative humidity range was 0 to 100 percent, effective up to 230°F. A temperature range from 10 to 170°F with an accuracy of ± 3 percent of full scale was provided by this indicator.

4. EXPERIMENTAL PROCEDURE

The experimental procedure which has been developed for the experimental equipment used in this research program for the substitution of fog oil with diesel fuel can be divided into three phases: (1) preliminary procedures, (2) operating procedures, and (3) standby or holding procedures.

4.1 Preliminary Procedures.

Prior to any test run, certain procedures were followed to insure that the equipment and system provided meaningful results. If the sand bath was cold or was not at the desired temperature, the air flow to the bath and heater controls was adjusted until the desired temperature was attained. Since the air which fluidzes the sand bath expands as it passes over the electrical heaters and upward through the sand bath, the higher the sand bath temperature the lower the air input to the sand bath to maintain a uniform bath temperature. This adjustment of air flow was done by either closing the inlet valve to the sand bath or opening a bypass valve provided in the supply line.

After the sand bath had been brought to the desired temperature, the powerstat supplying energy to the electrical heating tape on the discharge line was set at the desired voltage output for the conditions required for the test. The temperature was monitored by the thermocouple installed beneath the heating tape and insulation.

Approximately one hour prior to the first test to be run after the system had been placed in a holding or shutdown mode the helium-neon lasers and laser power meters were activated to provide sufficient time for the system to stabilize. The outputs from the power meters were monitored on the two-channel strip recorders.

If the material remaining in the feed lines, vaporizer and discharge line were not the same as the smoke material to be used in a given test, the system was operated at the conditions of the desired tests for at least 15 minutes in order to displace all the residual material in the system. If the system had been placed in a holding or shutdown mode, the water in the feed line, vaporizer and discharge line was displaced with the smoke material being investigated in the next experimental test.

After the displacement of the residual material with the smoke material of the next test, the system was cleared of smoke until the laser power meters indicated that the system was clear.

After the system had been cleared of smoke, the collection trays for any liquid discharged from the nozzle were tared prior to placement beneath the discharge nozzle.

4.2 Operating Procedures.

After the preliminary procedures had been completed, the system was ready for an experimental test. The following data were recorded on the data sheet just prior to startup:

- Date and test number
- Relative humidity and temperature in the wind tunnel
- Smoke material and object of test
- Smoke chamber configuration and type of discharge nozzle
- Operating mode of exhaust and internal fans
- Operating set points for the sand bath and heating tape on the discharge line
- Outside weather conditions
- Initial levels of the smoke material in the feed tanks
- Pressure of the nitrogen in the feed tanks

Just prior to startup, all recorders were marked with the date and test number. Startup was accomplished by opening the valves of the flow meters for the smoke material to be studied and the desired flow meter settings were set by manually adjusting the proper valves.

During the test run, the following data were noted on the data sheet:

- Time and initial temperature of the sand bath

- Pressure of the smoke material being fed to the vaporizer

- Flow meter readings

- Time that each target in the smoke chamber was legible

- Other comments which might assist in the interpretation of the experimental results.

Feed of the smoke material was stopped after the desired feed times by closing the appropriate valves in the feed line. The feed times varied between three (3) and five (5) minutes, whereas the experimental test period extended until the light signal received by the laser power meters essentially returned to the initial reading at the start of the test.

At the conclusion of the experimental test, the following data were recorded on the run sheet:

- Level of the smoke materials in the feed tanks

- Quantity of any liquid collected in the trays placed beneath the discharge nozzle

- Temperature of the smoke material just upstream from the inlet to the discharge nozzle.

4.3 Shutdown and Holding Mode Procedures.

At the conclusion of the test period, the smoke chamber and exhaust stack were cleared of any residual smoke by opening the smoke chamber at the end where the discharge nozzle was located. If another test was scheduled to be run, the preliminary procedures were repeated. If the system was to be placed in a holding mode, i.e., the sand bath would be maintained at or near the temperatures required for the next test, the common feed line to the vaporizer, the vaporizer and the discharge line would be purged with distilled water to displace all residual smoke material. This procedure was instituted to prevent plugging of the vaporizer coil with carbon formed by the thermal cracking of diesel fuel or fog oil after one vaporizer coil was plugged with a carbon-like material when fog oil remained in the coil at elevated temperatures for an extended period of time.

If the sand bath was to be shutdown for any reason such as system maintenance, system changes or the weekend, the electrical heaters were deactivated. Air supplied by the air pump was increased gradually as the temperature of the sand bath decreased. Air flow was continued until the temperature of the sand bath decreased to below 392°F (200°C) to prolong the life of the electrical heaters. Only after the temperature dropped below this value was the air pump shutdown. During the cooldown of the sand bath, the

exhaust fans, light transmission measuring systems, nitrogen pressure and the electrical heating tape on the discharge line were also shutdown.

5. EXPERIMENTAL RESULTS

In this experimental program on the substitution of fog oil with diesel fuel using a thermomechanical approach, several variables or additives which could affect the condensation and growth process through control of the superheat of the diesel fuel and four (4) nozzle designs have been studied. Variables which have been studied include various levels of superheat for the diesel fuel, feed rate, and feed duration for the smoke materials. Additives which have been studied include water, 10 percent by weight sodium chloride solution, talc and air with the addition generally being made either by premixing or postmixing the additive with the diesel fuel. Nozzle designs and configurations used included a standard venturi nozzle (0.125-inch throat), open tube nozzles (0.117-inch and 0.18-inch openings) and a mini-venturi/ eductor nozzle (0.060-inch throat).

The two basic smoke materials used in this research program were diesel fuel and fog oil which were supplied by Oak Ridge National Laboratory, Oak Ridge, Tennessee. The properties of these smoke materials are presented in the Appendix.

A total of 132 test runs have been made in this experimental program. Of this total, the first 37 runs were used in establishing the physical setup and the operating procedures required to yield acceptable reproducible results. Some of the test runs have not been presented in this section for one or more of the following reasons:

1. The quantity of material discharged into the smoke chamber was insufficient to produce an obscuring smoke screen.

2. The temperature of the material discharged into the smoke chamber was less than the boiling end point of the smoke material.

3. A malfunction in a piece of experimental equipment during the test period which would bias the results.

4. The quantity of material discharged into the smoke chamber was excessive in the sense that meaningful data were not obtained.

5. The quantity of material and temperature of the smoke material discharged did not correspond to any other experimental data.

Thus, only those data which could be compared directly to show the effects of the operating variables, additives or nozzle design and configuration have been presented.

In the early stages of the research program it became very clear that reproducibility of the results was not being achieved to the level required. Only after changing some of the equipment and operating procedures so that the quantity of smoke material fed to the smoke chamber was known with greater precision was an acceptable degree of reproducibility achieved. The degree of

reproducibility that can be expected is illustrated in Figure 8. As shown by Figure 8, the experimental tests were made on different days to insure that the external ambient conditions such as wind velocity and direction do not affect the results.

5.1 Effect of Superheat.

In the early stages of the research effort, experimental results which were obtained demonstrated that as the superheat of diesel fuel was increased the quality of the smoke produced decreased. This effect of superheat on the quality of smoke produced from diesel fuel discharged from a standard venturi nozzle having a 0.125-inch throat is shown in Figure 9. Although the expected trend is shown by this figure, the results should be interpreted with caution since the exact quantity of vapor discharged into the smoke chamber was not known. The effect of superheat could be even greater for the higher degrees of superheat because of less vapor being condensed in the nozzle in bringing it up to operating temperature. Any liquid formed in the nozzle drops out upon discharge and does not contribute to formation of smoke.

The effect of superheat on the quality of smoke produced from diesel fuel discharged from a mini-venturi/eductor with aspirated air is shown in Figure 10. In this case, the quantity of vapor discharged during each test is known with reasonable accuracy so that a greater degree of confidence can be placed in the results. The effect of superheat on the smoke quality does not appear so pronounced when air is aspirated at the discharge nozzle as it does when the diesel fuel is discharged from a standard venturi nozzle. When air is aspirated at the discharge nozzle, excellent mixing between the diesel fuel and air is achieved to enhance the heat transfer between the air and diesel fuel. Furthermore, the increased velocity at the higher temperatures augments the aspiration of air, thereby enhancing heat transfer between the air and diesel fuel.

The effects of superheat on the quality of smoke produced from diesel fuel and fog oil are illustrated in Figures 11 and 12. These two sets of runs differ from the runs in Figure 10 by the fact that the results in Figures 11 and 12 are without aspirated air. Thus, in Figure 11, the diesel fuel vapor was discharged from a mini-venturi/eductor, with the eductor closed, at temperatures of 700, 820 and 912°F which represent superheats of 50, 170 and 262°F, respectively. Similarly, as shown in Figure 12, fog oil was discharged from a mini-venturi/eductor, with the eductor inlet closed, at temperatures of 856 and 924°F compared to the boiling end point of 870°F. For the diesel fuel, the test results indicate that a superheat of about 170°F produced a better quality smoke than lower or greater degrees of superheat. Similarly, as shown by the results for fog oil in Figure 12, a superheat of 54°F produced a slightly better smoke than a wet or unsaturated fog oil. It thus appears that there is an optimum level of superheat, which is not surprising, since the number of nuclei formed, rates of condensation, evaporation or coalescence and degree of cooling by admixing with aspirated air are all interacting parameters.

Comparisons of the smoke quality produced from fog oil and diesel fuel discharged at respectively the same degrees of superheat (about 50°F) from

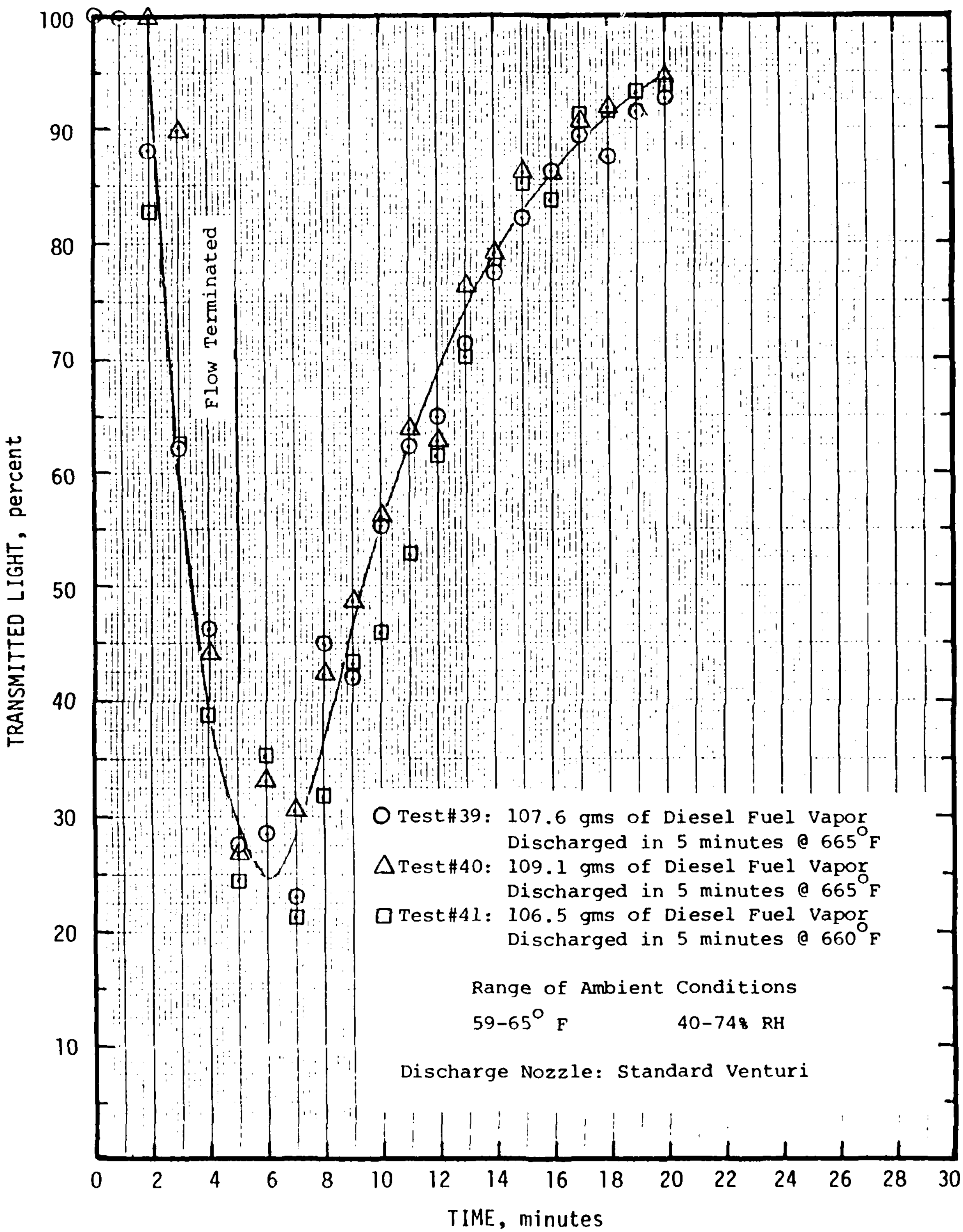

Figure 8. Comparison of Smoke Quality Produced from Diesel Fuel under Similar Conditions

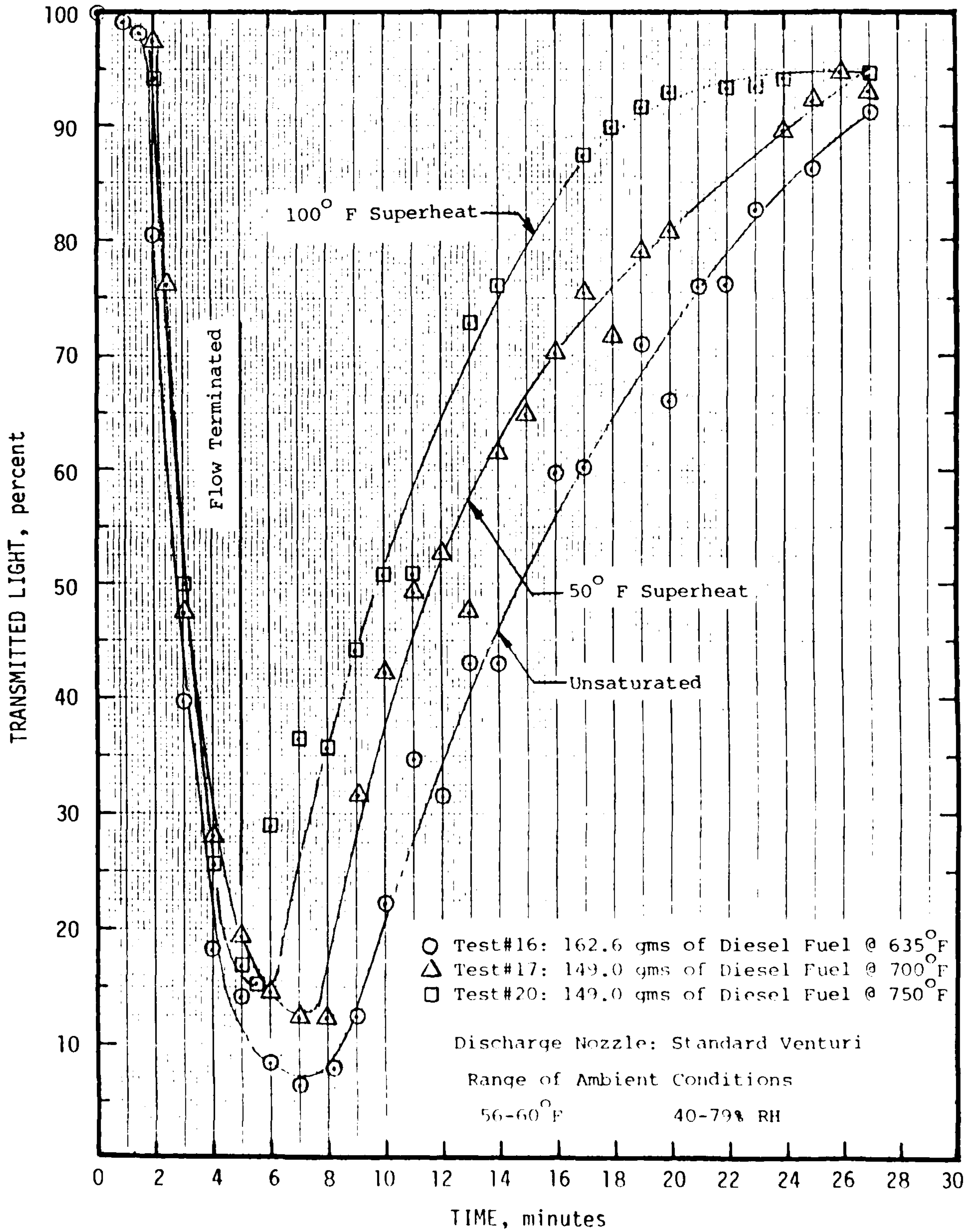

Figure 9. Effect of Superheat on Quality of moke Produced from Diesel Fuel Discharged from a Venturi Nozzle

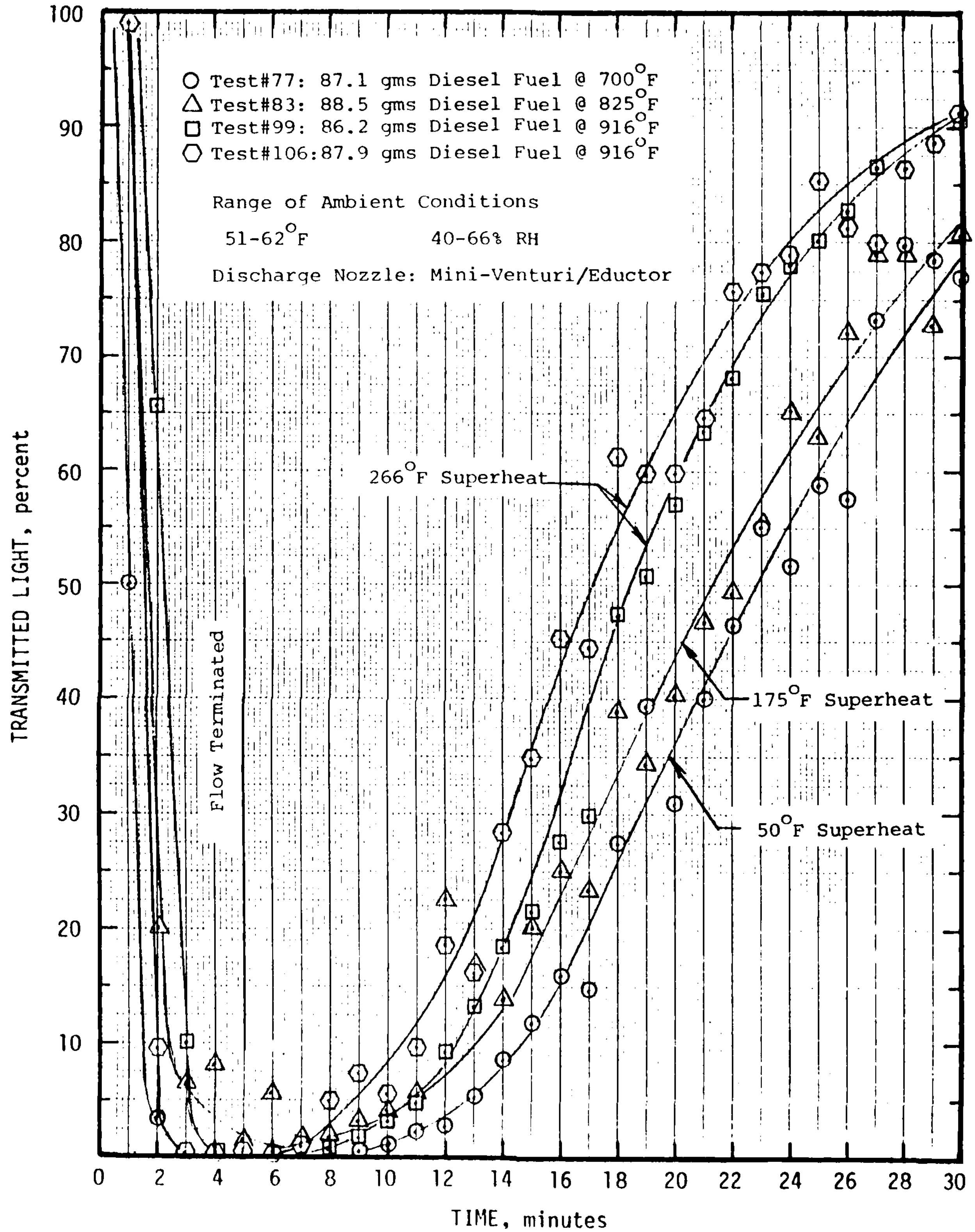

Figure 10. Effect of Superheat on Quality of Smoke Produced from Diesel Fuel with Entrained Ambient Air

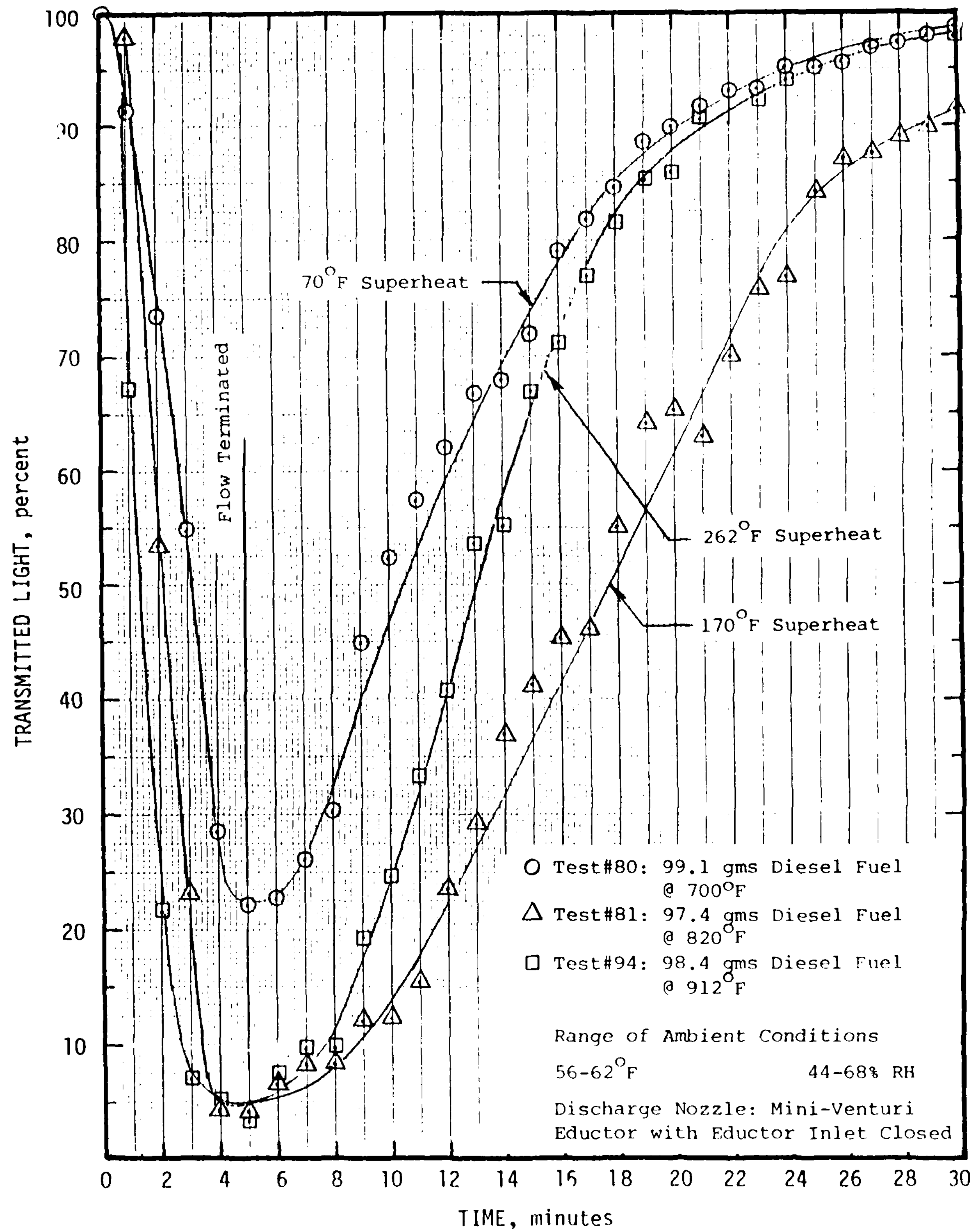

Figure 11. Effect of Superheat on Quality of Smoke Produced from Diesel Fuel without Entrained Air

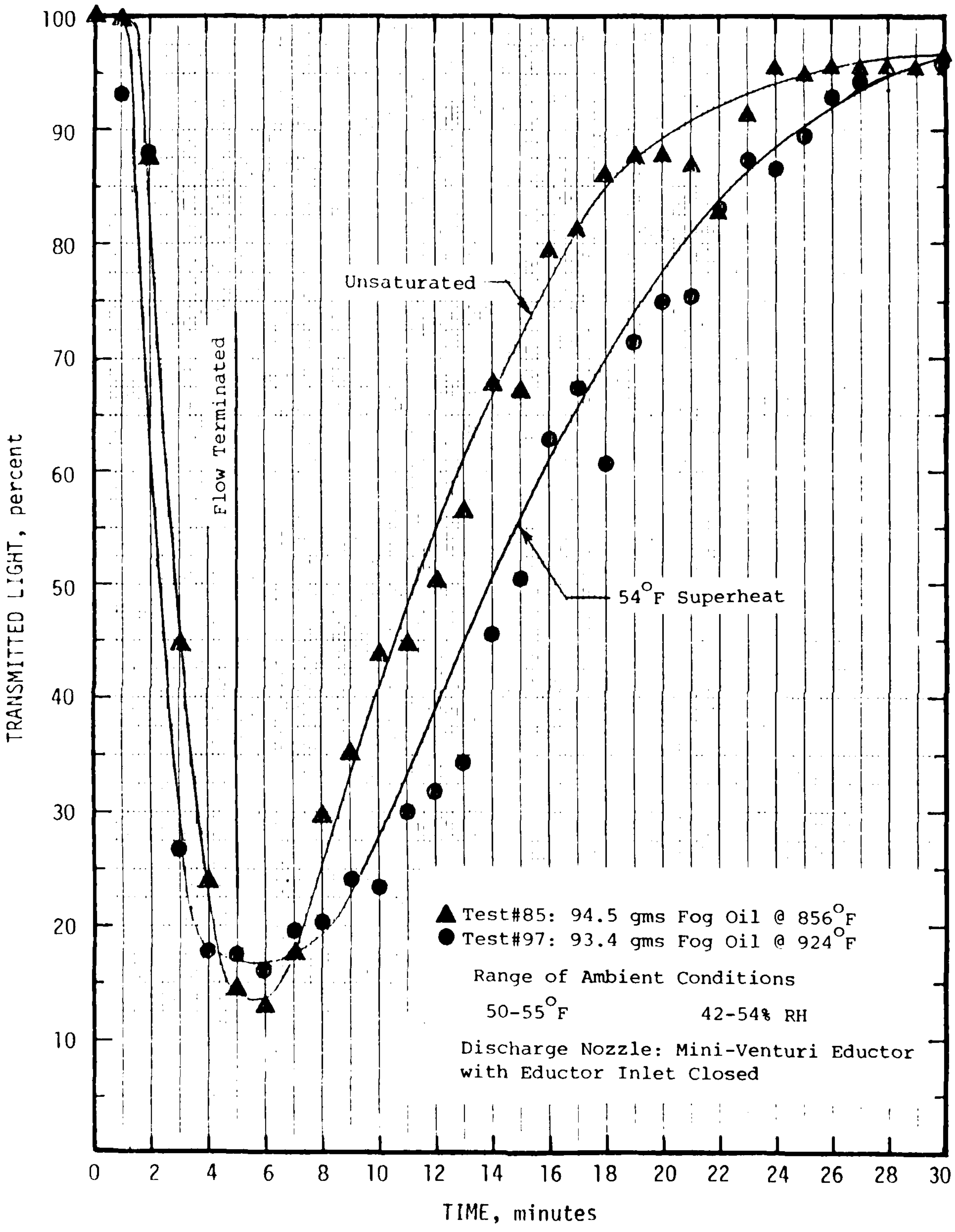

Figure 12. Effect of Superheat on Quality of Smoke Produced from Fog Oil without Entrained Air

the eductor nozzle with the entrained air port blocked-off, are shown in Figure 13. Under these conditions, the fog oil appears to be better. This test was repeated with the eductor port open to aspirate air. In this case, Figure 14, the diesel fuel produced a more persistent (near-field) smoke which is somewhat surprising since the degrees of superheat were almost the same and the amount of air entrained was probably not more than 10 percent greater for the diesel fuel. Although the "leap-frog" approach has prevented the systematic evaluation required to verify these results, the entrainment of air in the mini-venturi/eductor nozzles yields a marked improvement in the smoke quality regardless of the smoke material used.

5.2 Effect of Nozzle Design and Configuration.

The effects of nozzle design and configuration on the quality of smoke generated from diesel fuel and fog oil are illustrated in Figures 15 and 16. As shown in Figure 15 for diesel fuel discharged at temperatures between 912 and 924°F, the mini-venturi/eductor with aspirated air produced the best quality smoke and the mini-venturi/eductor with the eductor inlet closed produced the poorest quality smoke. The discharge through an open tube nozzle (3/16-inch tube) produced a smoke quality which was almost as good as that discharged from the mini-venturi/eductor with entrained air. This trend was also observed in other tests in which a comparison could be made in the nozzle design and configuration. Results for fog oil discharged through these nozzles are somewhat less conclusive. Although the yields with the open discharge tube and the entrained air eductor are comparable, the persistence of the former is more akin to the eductor without air aspiration.

Further comparisons of the effect of operating parameters on the quality of smoke produced from diesel fuel discharged from different nozzle configurations are presented in Figure 17. In these four runs, diesel fuel was discharged at temperatures varying between 675 and 700°F, and at rates varying between 12.4 and 19.8 g/min. Two of these runs were from the eductor nozzle without entrained air (eductor inlet closed) and two were with entrained air. Over this range of variables, the quality of smoke produced from diesel fuel was significantly better with entrained air.

A more direct comparison of the smoke produced from diesel fuel and fog oil discharging from a mini-venturi/eductor nozzle with air entrainment at similar flow rates and identical discharging temperatures is given in Figure 18. Although the diesel fuel was discharged with a superheat of about 266°F as compared to the fog oil discharging with a superheat of about 46°F, the density and persistence of the smokes produced from both materials appear to be equal. This result would at first appear to be contradictory in that the diesel fuel was discharged at a much greater superheat than the fog oil. However, the amount of air entrained by the diesel fuel through the venturi/eductor was estimated to be about 25 percent greater than in the case of the fog oil. This greater quantity of air appears to be sufficient to offset the effect of greater superheat.

5.3 Effect of Additives.

Several different additives have been studied to evaluate their effect upon the quality of smoke produced from diesel fuel. These additives

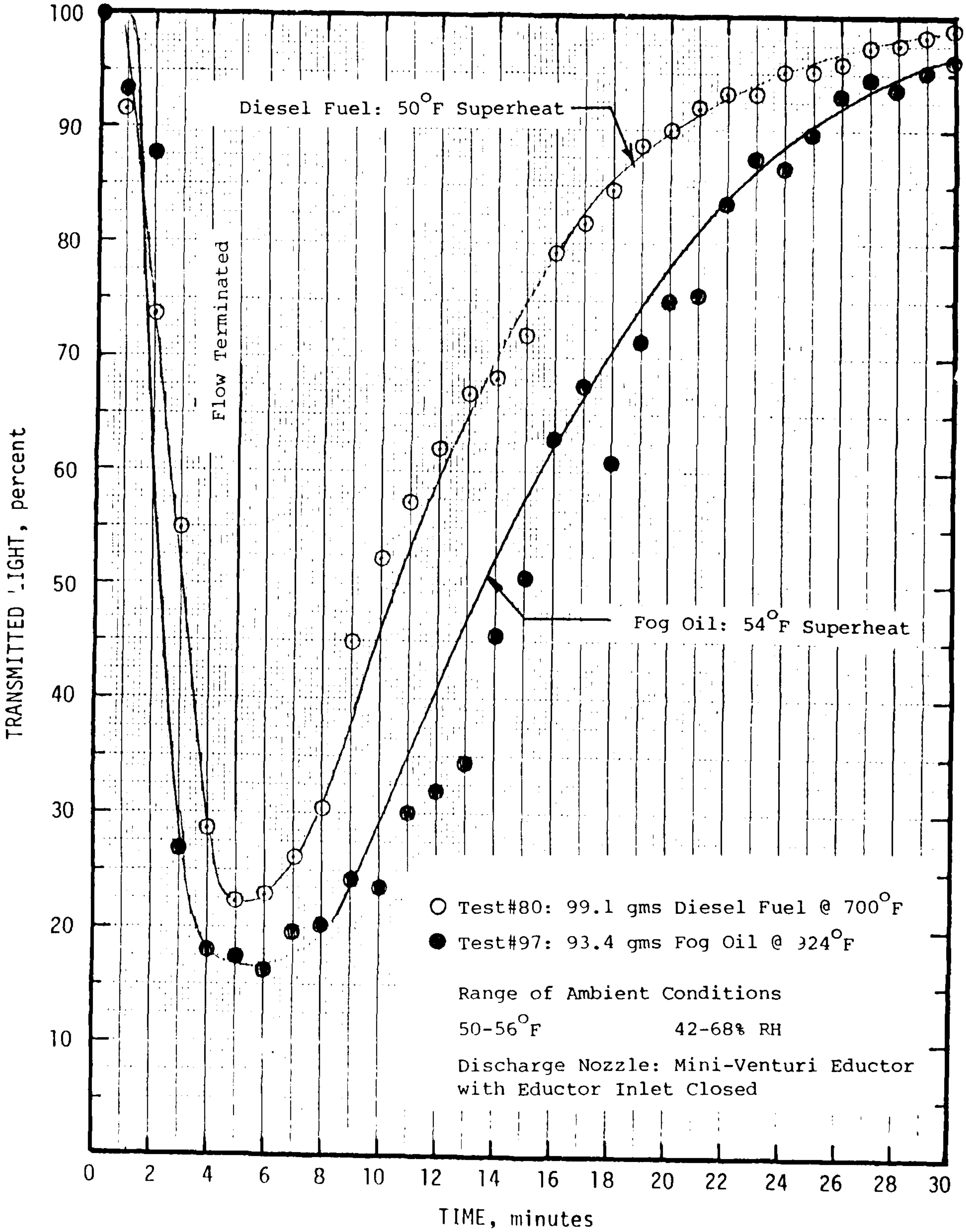

Figure 13. Comparison of Quality of Smoke Produced from Fog Oil and Diesel Fuel at Similar Degrees of Superheat without Entrained Air

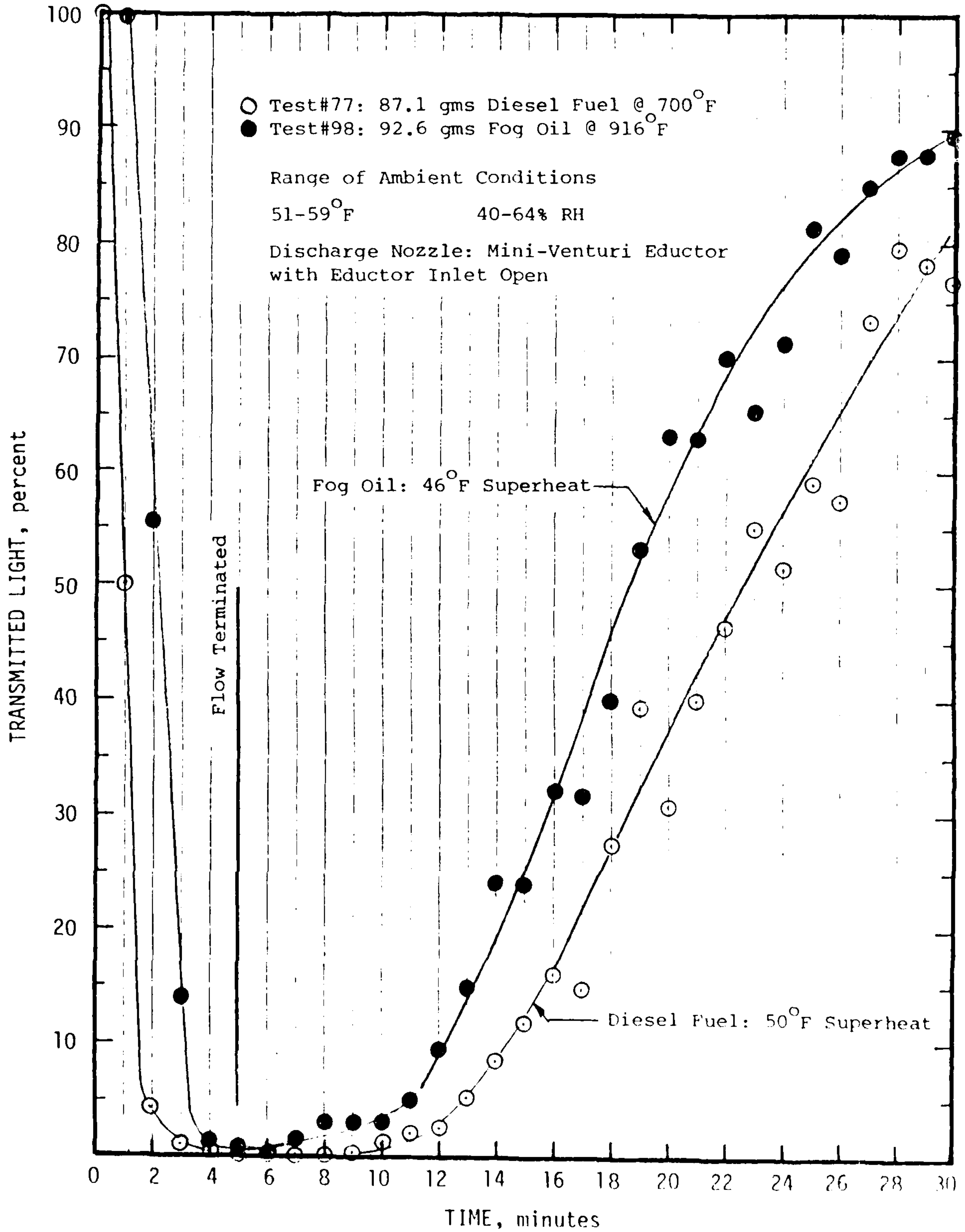

Figure 14. Comparison of Quality of Smoke Produced from Fog Oil and Diesel Fuel with Entrained Ambient Air and at Similar Degrees of Superheat

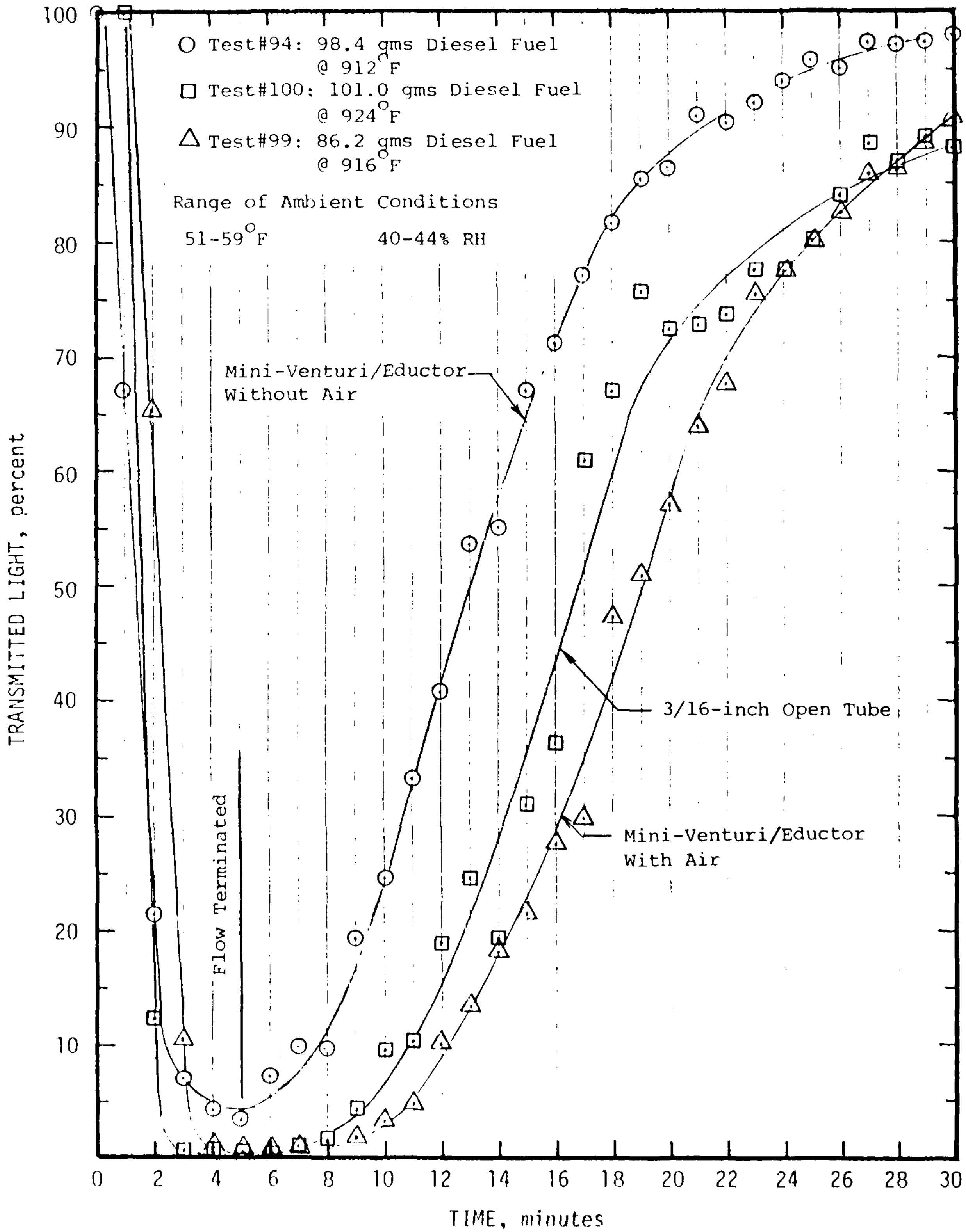

Figure 15. Comparison of Quality of Smoke Produced from Diesel Fuel Discharged from Three Types of Nozzles

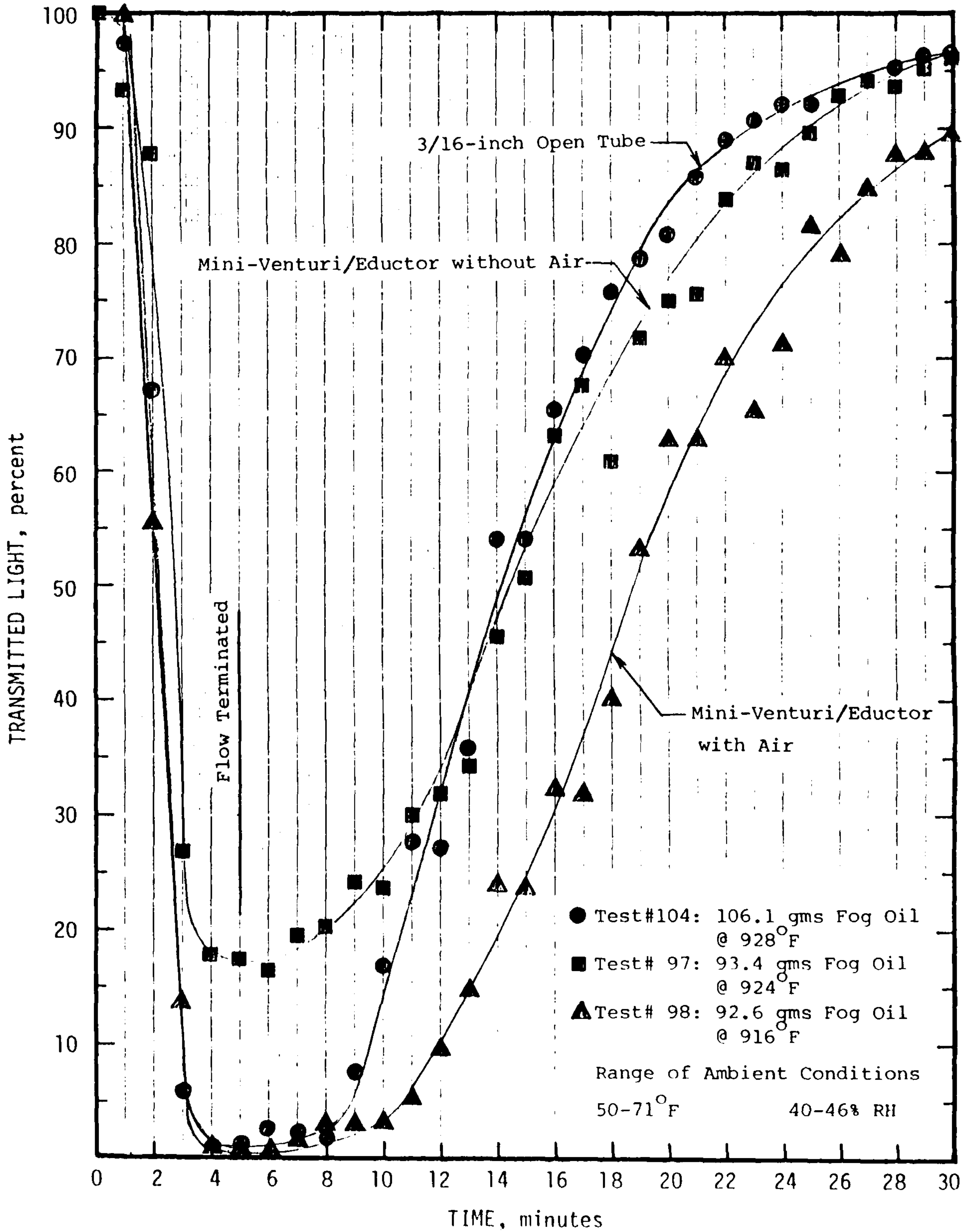

Figure 16. Comparison of Quality of Smoke Produced from Fog Oil Discharged from Three Types of Nozzles

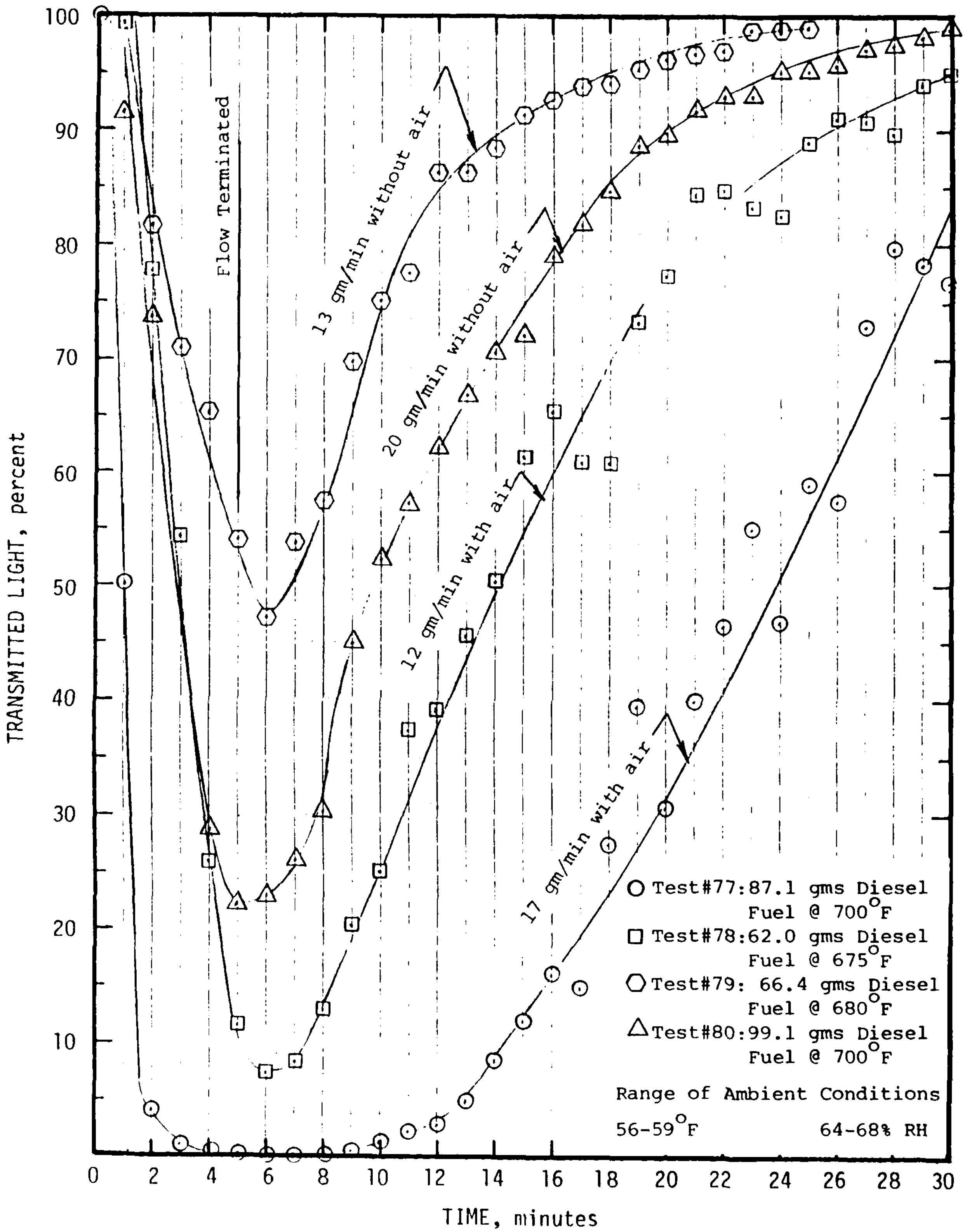

Figure 17. Comparison of Quality of Smoke Produced from Diesel Fuel Discharged with and without Entrained Ambient Air

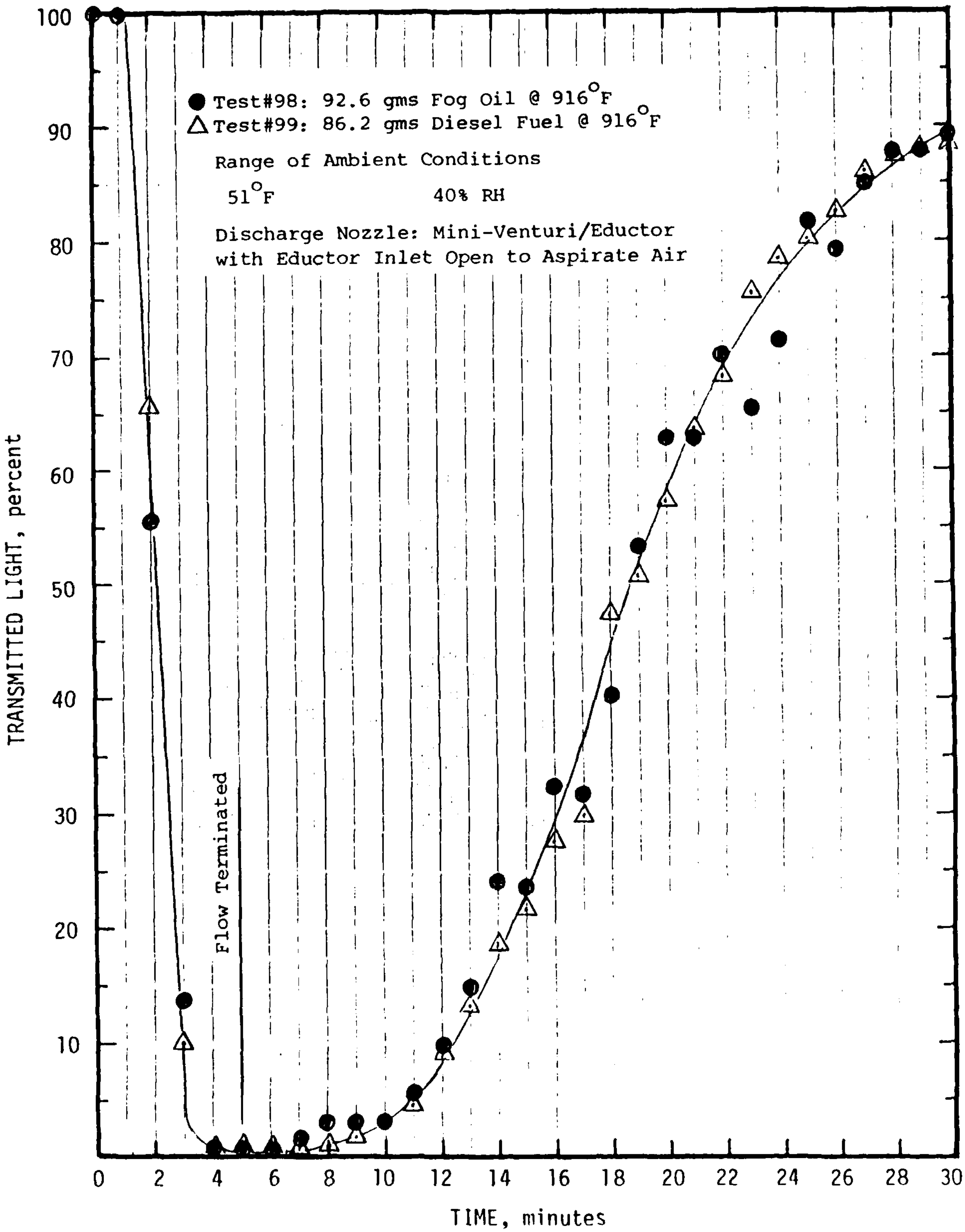

Figure 18. Comparison of Quality of Smoke Produced from Fog Oil and Diesel Fuel with Entrained Ambient Air

were either mixed with the diesel fuel before being evaporated in the vaporizer or mixed with the diesel fuel vapors at or within the discharge nozzle. Additives which have been included in this research effort were water, a 10 percent by weight sodium chloride solution, cold air and talc. Ambient air has not been included in this section since it was discussed in the section on the effect of nozzle design and configuration.

The experimental results from tests using diesel fuel and water, with the water being mixed with the diesel fuel before vaporization, as the smoke material and discharging from an open tube nozzle are presented in Figure 19. Although the data were too erratic to define discrete curves for each test--so that only a single, dashed curve is used to indicate the data trend--it appears that the amount of water premixed with the diesel fuel does not affect the light transmitted.

A direct comparison of the smoke produced from diesel fuel and diesel fuel premixed with distilled water when discharging from a venturi nozzle under similar conditions is presented in Figure 20. In this case, the quality of the smoke with or without water is similar. By way of further comparison, the dashed curve from Figure 19 for the open tube nozzle is also shown on Figure 20, which again indicates that vapors of smoke material discharged from an open tube nozzle produce a more dense smoke. However, it should be pointed out that the temperature of the vapors discharged from the open tube nozzle was near saturation (650°F) as shown in Figure 19, whereas for the venturi nozzle the discharge temperature was more than 100°F above saturation as shown by Figure 20.

Tests in which diesel fuel vapors were postmixed with water at the discharge nozzle were made to evaluate this effect on smoke quality and to compare the results with those of modified diesel fuel consisting of a premix with water. The results which are presented in Figure 21 indicate that the quantity of water postmixed with diesel fuel does not affect the quality of smoke. This observation is consistent with that observed in the tests in which water was premixed with the diesel fuel prior to vaporization as shown by Figure 19. It is clearly evident that premixing water with diesel fuel prior to vaporization produced a better smoke than postmixing water with the diesel fuel vapors.

A single test was made to evaluate the effect of cold entrained air on the quality of smoke produced from diesel fuel. The cold air was obtained by chilling compressed air contained in a pressurized bottle in a freezer and subsequently maintaining it at about 0°F by immersing it in a chilled calcium chloride solution. During the run, the air bottle was connected to the side inlet of the mini-venturi/eductor nozzle; a manual valve on the cylinder was used to regulate the flow of cold air to the discharge nozzle. The results of this test are presented in Figure 22, which also includes the results of a similar test using diesel fuel with entrained air at ambient temperature for comparison. The anticipation of a better smoke produced with cold entrained air than with ambient entrained air did not result. Approximate calculations, however, indicated that the quantity of cold air entrained in this test was only about 20 percent of that for the case of ambient entrained air. If so, then the results are neither contradictory nor surprising.

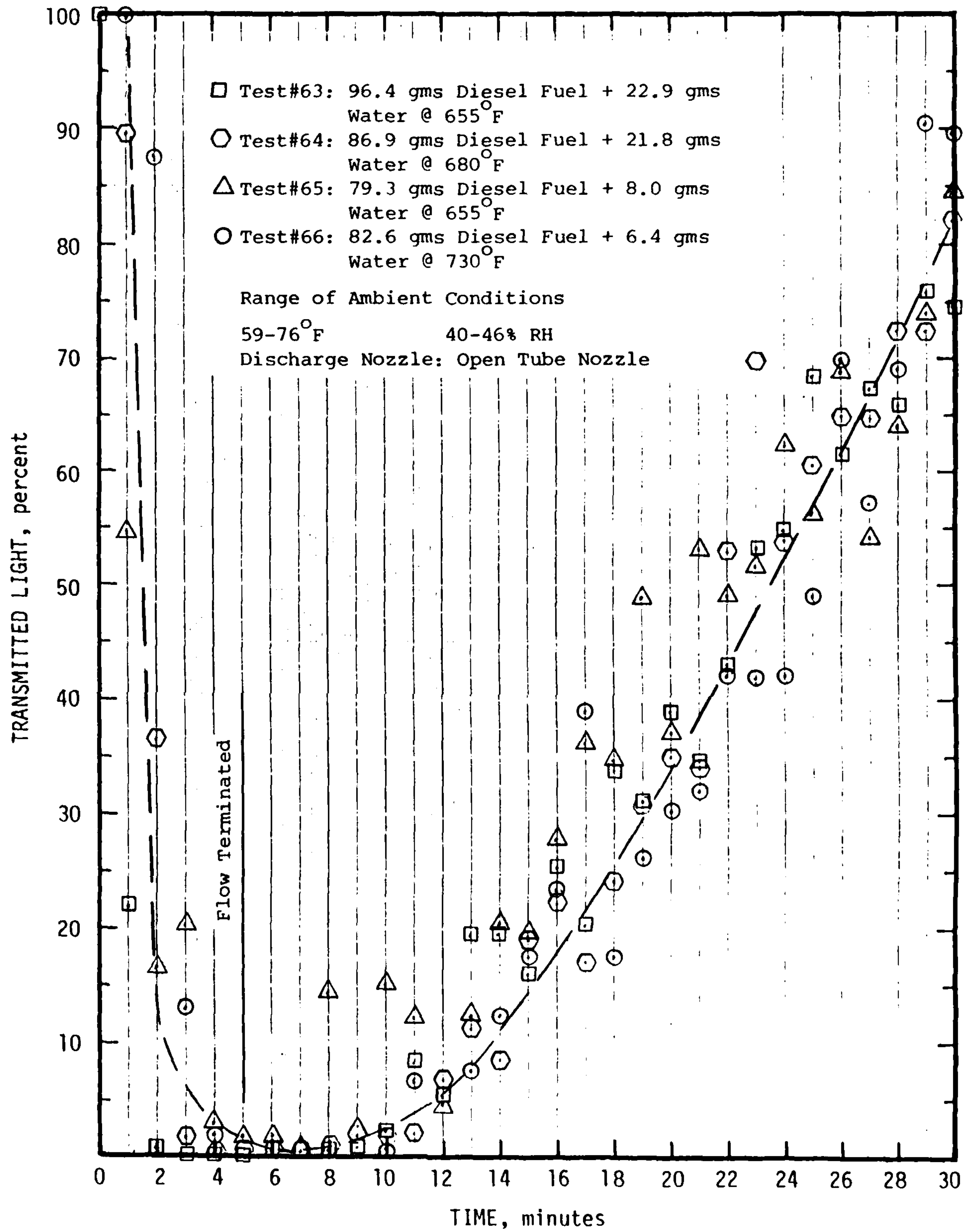

Figure 19. Quality of Smoke Produced from Diesel Fuel Premixed *with Water Prior to Vaporization*

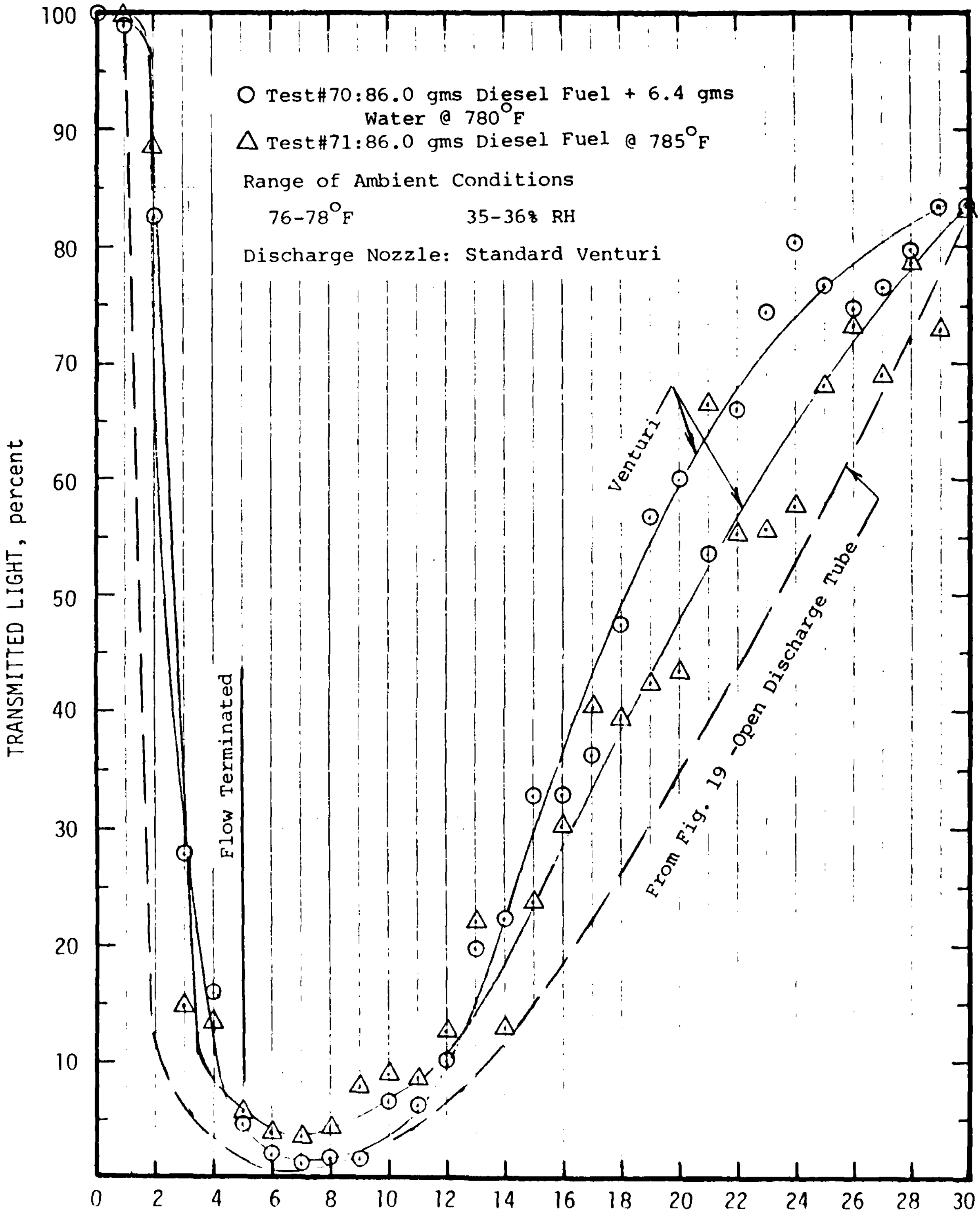

Figure 20. Comparison of Quality of Smoke Produced from Diesel Fuel and Diesel Fuel Premixed with Water Prior to Vaporization at Similar Conditions

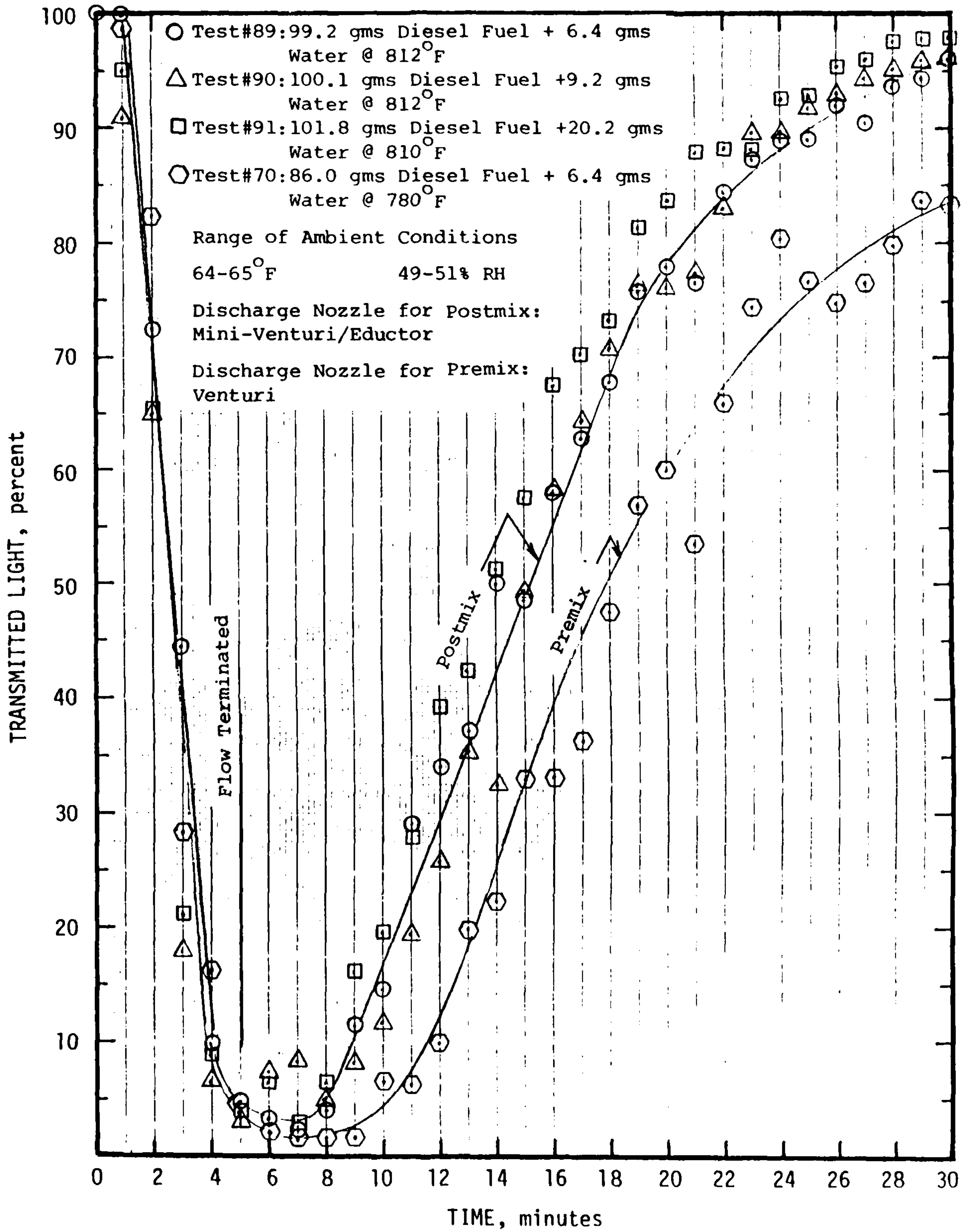

Figure 21. Comparison of Quality of Smoke Produced from Diesel Fuel Vapors Postmixed with Water at Discharge Nozzle

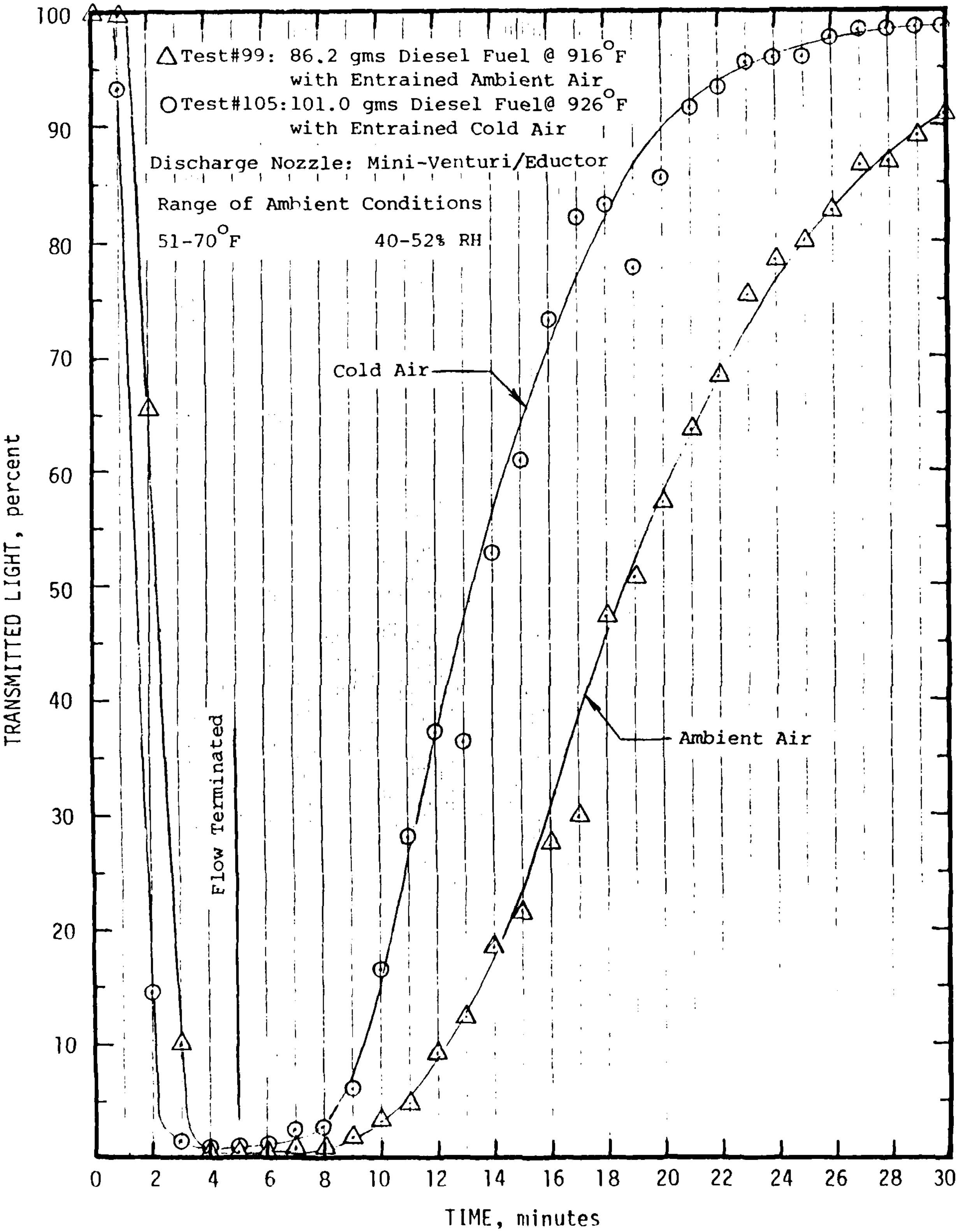

Figure 22. Effect of Temperature of Entrained Air on Quality of Smoke Produced from Diesel Fuel

Four tests were made to evaluate the effect of adding a solid in solution on the quality of smoke produced from diesel fuel. A 10 percent by weight sodium chloride solution was added to the diesel fuel either by premixing with the diesel fuel prior to vaporization or by postmixing with the diesel fuel vapors at the discharge nozzle. The results of two tests in which the 10 percent sodium chloride solution was added to the diesel fuel prior to vaporization are presented in Figure 23. These tests were made using the mini-venturi/eductor nozzle with the eductor open to the air for direct comparison with a test made using water premixed with diesel fuel prior to vaporization. Considering that the tests in which sodium chloride was premixed with the diesel fuel discharged less diesel fuel into the smoke chamber, this comparison indicates that the addition of solids in a solution does not improve the quality of smoke. The lower quantity of diesel fuel discharged in the tests using an additive of sodium chloride solution (81.9 and 66.2 g) was caused by the reduction in flow rate of diesel fuel as sodium chloride apparently restricted flow by precipitating from the vapors in the vaporizer and discharge line. As indicated in Figure 23, the quantity of diesel fuel discharged into the system was 92.3 g.

The results of two tests in which the 10 percent solution of sodium chloride was added to the diesel fuel vapors at the discharge nozzle are presented in Figure 24. The sodium chloride solution was added to the diesel fuel vapors through the eductor inlet port of the mini-venturi/eductor. The results of the tests in which the solution was premixed with the diesel fuel are also presented in Figure 24 to provide a direct comparison of the methods in which the solution is added to the diesel fuel. Although the quantity of diesel fuel (about 93 g) was greater than that added in the tests with premixing (81.9 and 66.2 g), the addition of solution to the diesel fuel prior to vaporization produced a better quality smoke. This result is consistent with that observed for tests involving the addition of water either by premixing with the diesel fuel prior to vaporization or by postmixing with diesel fuel vapors at the discharge nozzle (see Figure 21).

A direct comparison of the quality of smoke produced from diesel fuel postmixed with a 10 percent sodium chloride solution and from diesel fuel with entrained ambient air is presented in Figure 25. This comparison illustrates that the quality of smoke, both in terms of yield and persistence, is enhanced when the diesel fuel is discharged with entrained air in a mini-venturi/eductor.

One very important consideration that should be mentioned concerning the use of solids in solution to enhance the quality of smoke produced from diesel fuel is that the solid will precipitate from the gas phase readily to adhere to metal surfaces. In all tests in which a 10 percent solution of sodium chloride was used as an additive to diesel fuel, restrictions in flow were observed in tests involving the premixing of solution with diesel fuel prior to vaporization and the diverging section of the discharge nozzle was coated with salt particles for all tests involving the sodium chloride solution. These problems with solid precipitation and nozzle coating would have to be addressed in the design of the smoke generators if salt solutions were to be considered as an additive to diesel fuel for smoke quality enhancement.

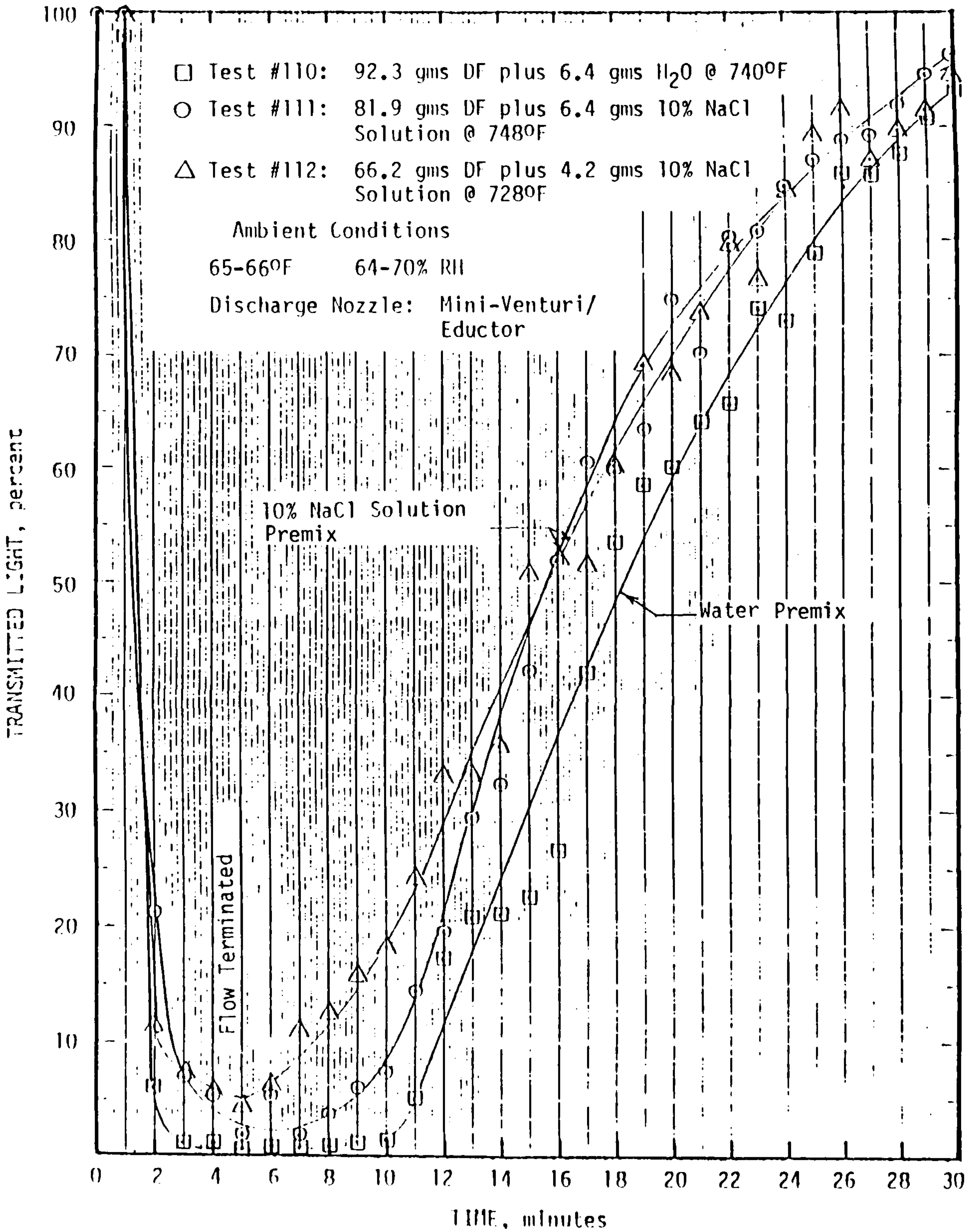

Figure 23. Effect of Solids in Solution on the Quality of Smoke Produced from Diesel Fuel Premixed with 10 Percent NaCl Solution and with Entrained Ambient Air

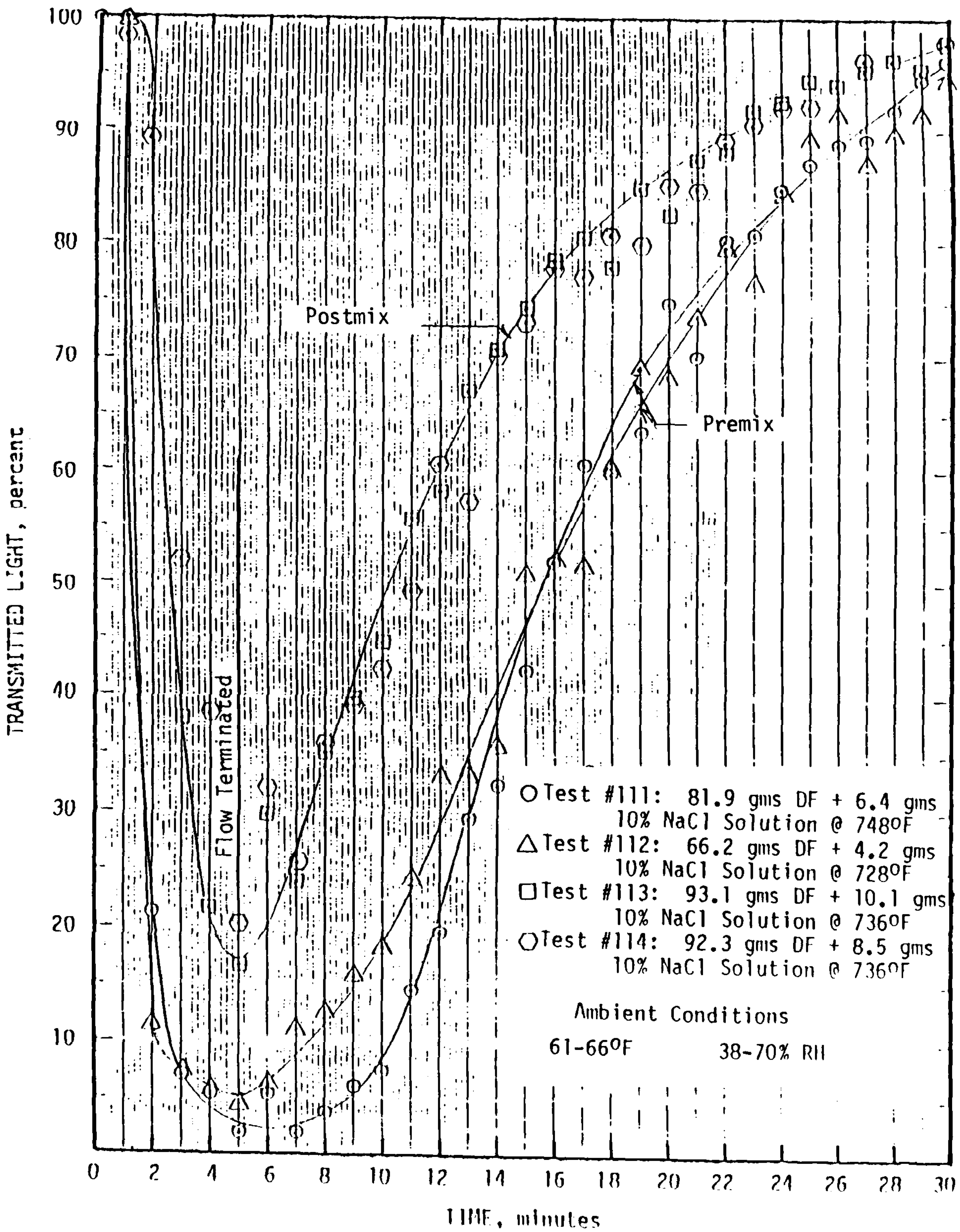

Figure 24. Comparison of Smoke Quality from Diesel Fuel Premixed and Postmixed with a 10 Percent Solution of Sodium Chloride

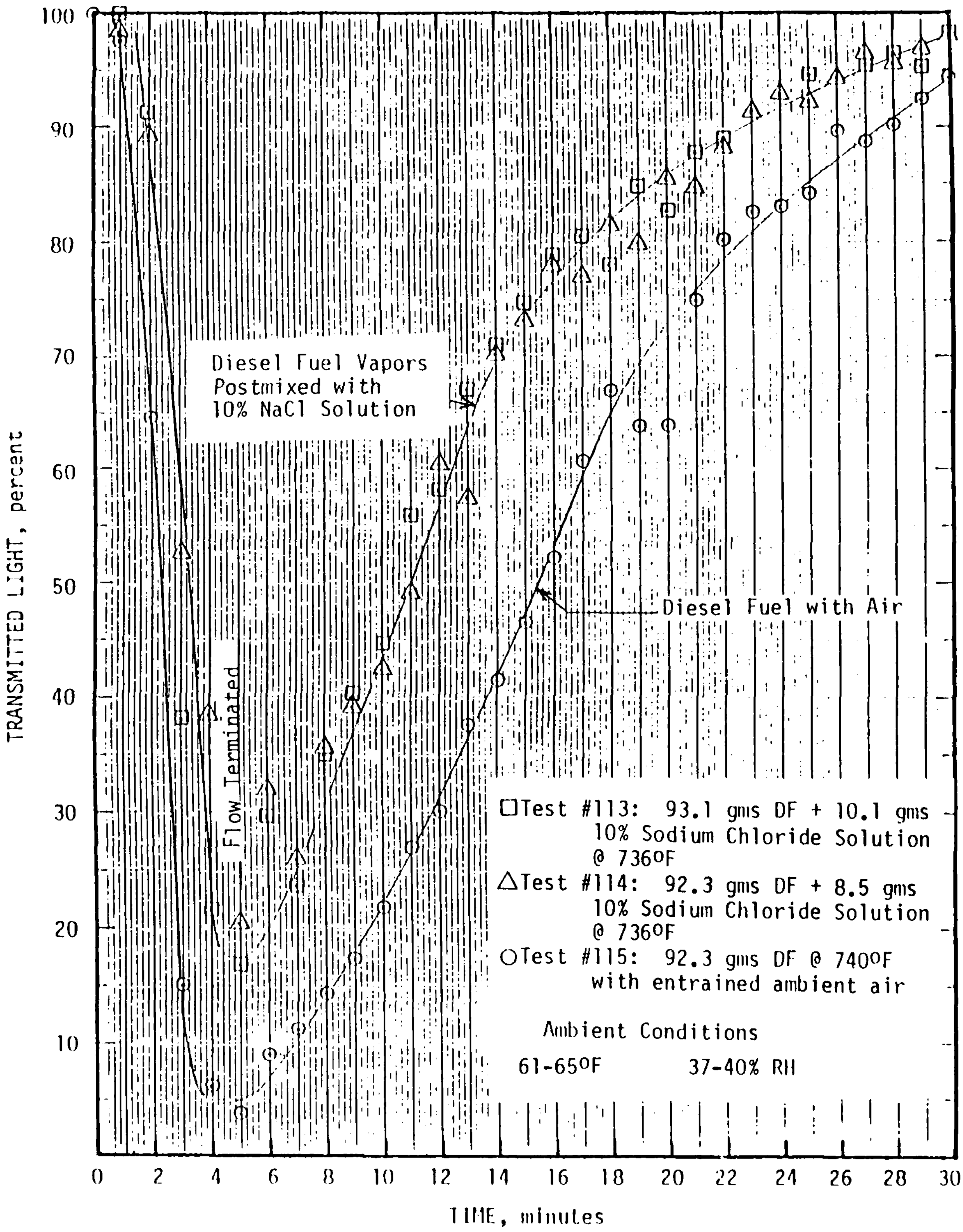

Figure 25. Comparison of Smoke Quality Produced from Diesel Fuel Postmixed with 10 Percent Sodium Chloride Solution and Diesel Fuel with Entrained Ambient Air

The addition of talc (Family Care Baby Powder) to the diesel fuel vapors within the mini-venturi/eductor was accomplished using nitrogen to fluidize the talc in a round-bottomed cylinder and to transport the talc to the inlet port of the eductor. Although the results are preliminary (only three tests have been made), it appears that the addition of talc enhances the yield and persistence of the smoke produced from diesel fuel as can be seen in Figure 26. The results of a test using diesel fuel mixed with about the same quantity of nitrogen which had been used to fluidize and transport the talc to the discharge nozzle are also included to show that the improvement in yield and persistence was not the result of nitrogen addition but rather the effect of adding talc. In fact, this combination of diesel fuel and nitrogen indicates that the nitrogen flow is less than the air flow which is aspirated when the side entry to the eductor is open to the atmosphere as demonstrated in Figure 22. The improvements in smoke quality by the addition of talc is believed to be the result of providing instantaneous nuclei for the condensation of diesel fuel vapors.

5.4 Effect of Discharge Rate.

A direct comparison of the effect of discharge rate for fog oil on the density and persistence of smoke is presented in Figure 27. The fog oil was discharged at rates of 21.2 and 34 g/min with discharge times of 5 and 3 minutes, respectively. Thus, essentially the same total quantity of fog oil vapor was introduced into the smoke chamber. Although the minimum light transmitted (or yield) was slightly better for the higher discharge rate, the persistence was not, conceivably because of more coalescence and dropout at higher discharge rates.

5.5 Smoke Quality in Exhaust Stack.

Results from the light transmittance system installed in the exhaust stack for the smoke chamber had been very erratic as indicated by the upper display (triangular points) in Figure 28. Since interpretation of such results is virtually impossible, a change in the operating conditions in both the wind tunnel and the smoke chamber was made in an attempt to improve the quality of results obtained from the light transmittance system located in the exhaust stack. In the first 115 tests, the primary blower for the wind tunnel proper was not used. By operating the blower near its lowest rate, a positive flow of air was induced through the wind tunnel proper, as well as through the smoke chamber but at a much lower velocity. The principal result was an increase in the draft through the vertical stack of the smoke chamber and consequently the smoke chamber itself. Test 131 in Figure 29 demonstrates the remarkable improvement over Test 121 in Figure 28, particularly in facilitating interpretation and direct comparison with other tests which will be made in the future. Although these conclusions are preliminary, it is anticipated that the change in operating procedure will become standard operating practice, henceforth.

5.6 Scatter of Smoke Particles.

The third photosensor and laser power meter installed in the latter stages of the program to measure scattered light at 90° to the light beam did

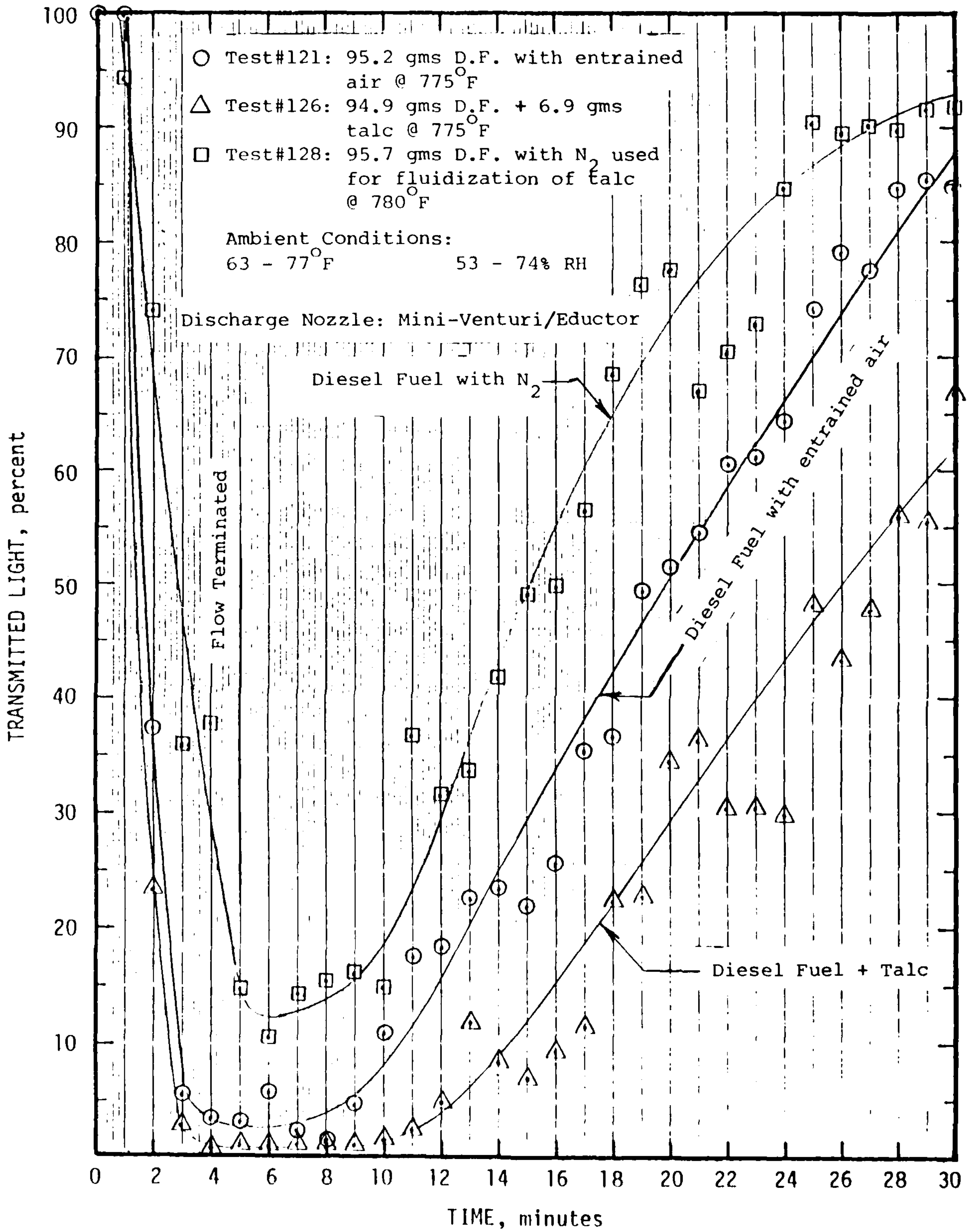

Figure 26. Comparison of Quality of Smoke Produced from Diesel Fuel Vapors Mixed with Talc at the Discharge Nozzle, Diesel Fuel with Entrained Air and Diesel Fuel with Nitrogen under Similar Conditions

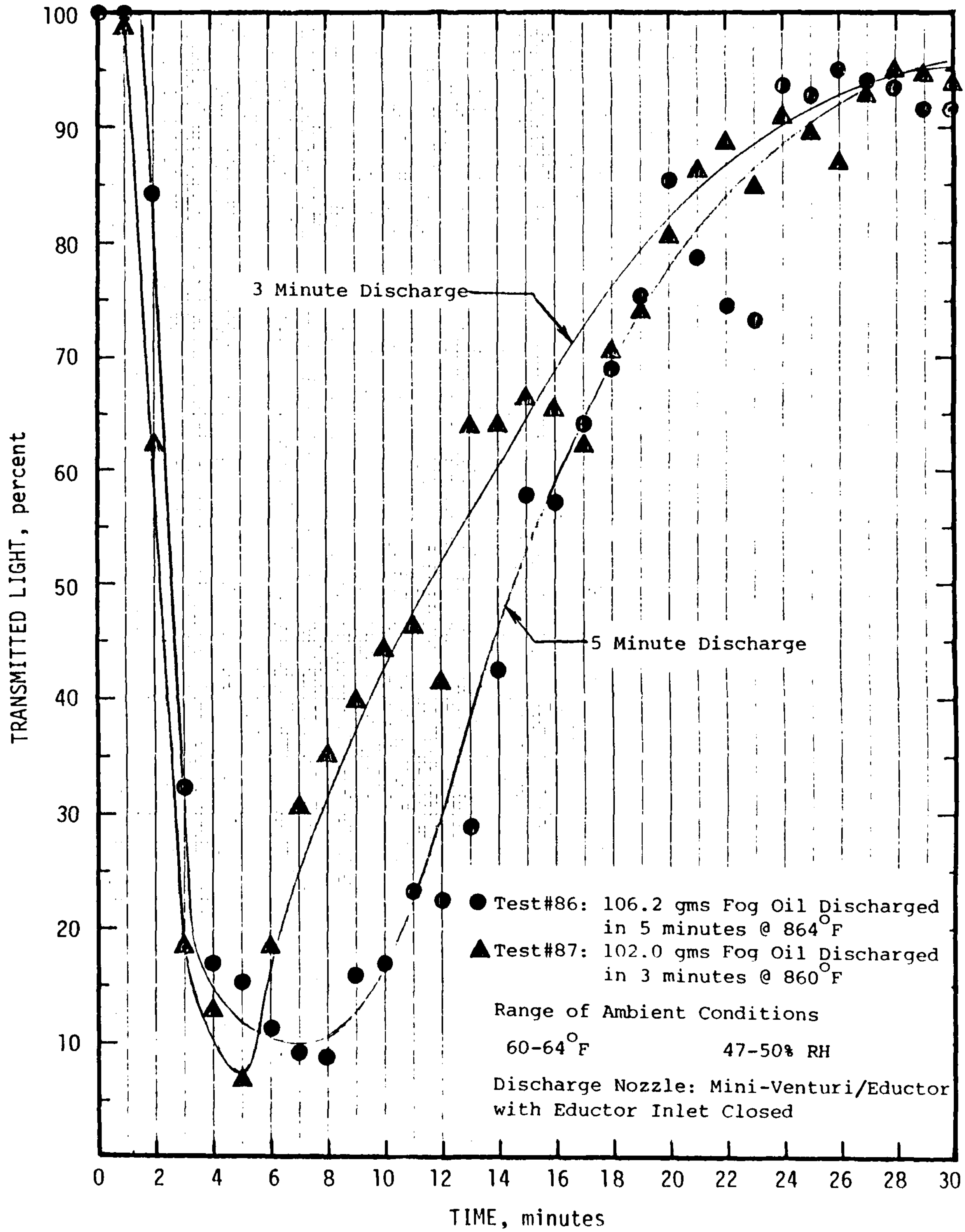

Figure 27. Effect of Discharge Rate of Fog Oil on Quality of Smoke

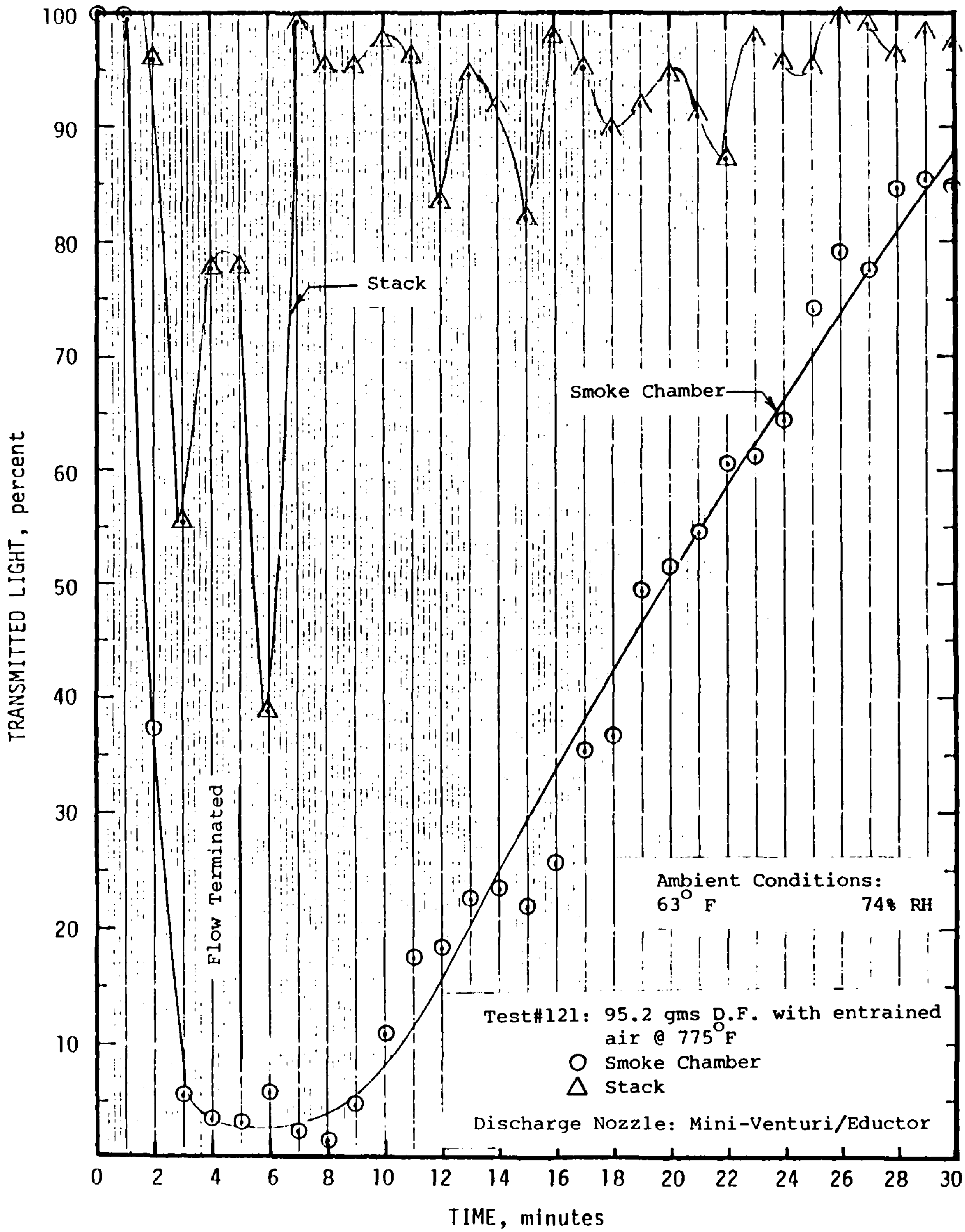

Figure 28. Quality of Smoke Produced from Diesel Fuel with Entrained Air without Wind Tunnel Blower Operating

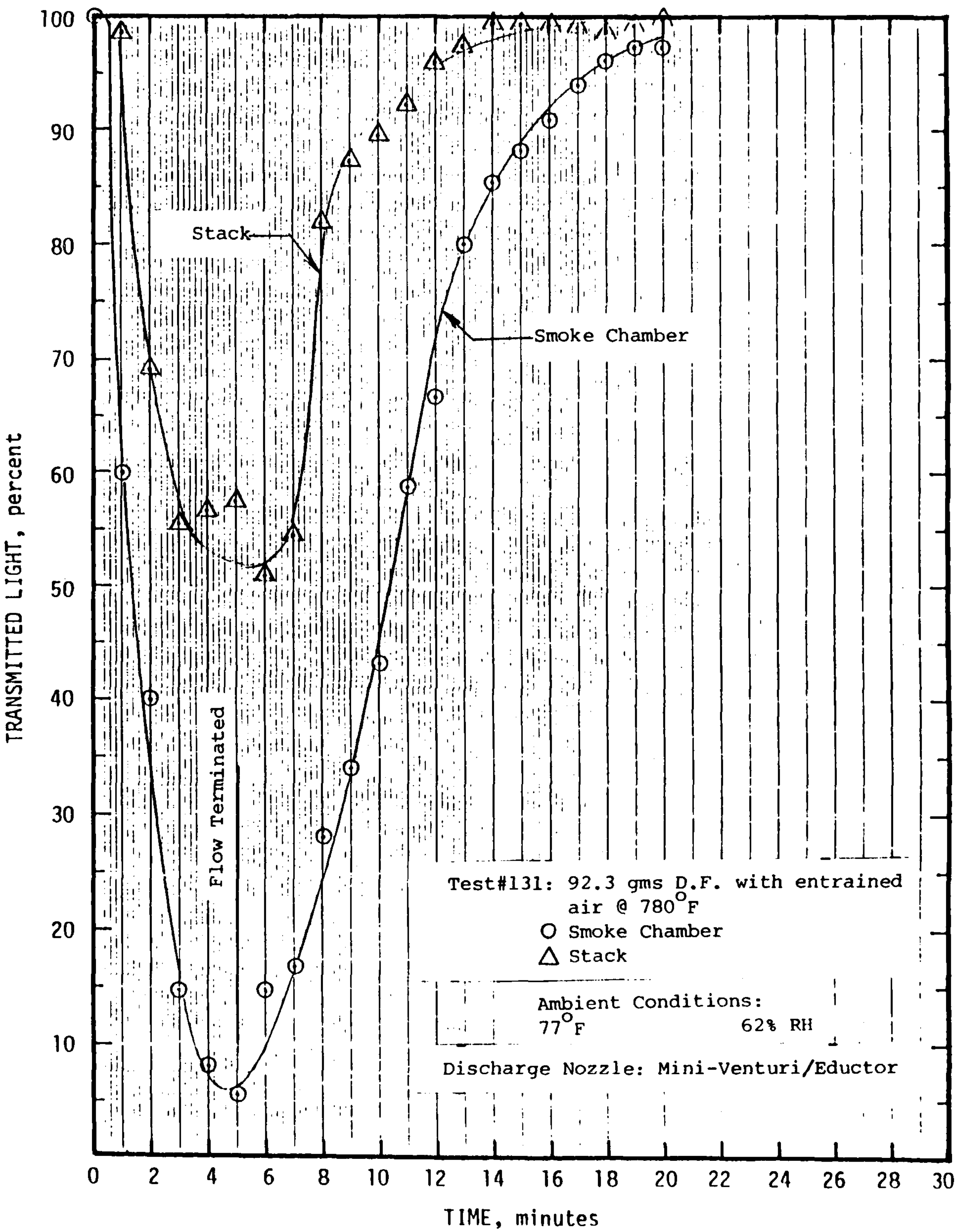

Figure 29. Quality of Smoke Produced from Diesel Fuel with Entrained Air with Wind Tunnel Blower Operating

not register in any of the 17 tests made after its installation for diesel fuel discharged at temperatures varying from 750 to 906°F, diesel fuel in combination with talc and fog oil discharged at 920°F. The absence of scatter for the diesel fuel/talc combination was somewhat surprising. More experimentation with the positioning of the laser power meter/photosensor for monitoring scattered light is indicated.

5.7 Visual Observations.

As stated previously, six (6) numbered targets were positioned in the smoke chamber so that visual observations of the smoke obscuration could be made. Times were noted when each numbered target was legible in the opinion of the observer. Obviously, there is some judgment required in what constitutes legibility of the target by the observer. The purpose of these observations is to provide some level of comparison between the transmission of light through the smoke and what one can actually see. Based on observations from 60 experimental runs, the average percent light transmitted when a target 18 in in the smoke could be read was 19.1 percent. The average percent light transmitted when it was possible to distinguish objects across the width of the smoke chamber (42 in) was 28.2 percent. In other words, if the percent light transmitted was less than 19.1 percent, then the observer could not read the numbered target positioned 18 in from the near wall. Likewise, if the percent light transmitted was less than 28.2 percent, objects on the opposite wall of the smoke chamber could not be distinguished with any degree of certainty.

6. CONCLUSIONS

Based on the experimental results obtained in this research effort on the substitution of fog oil with diesel fuel, it is concluded that:

1. The thermomechanical approach is a viable concept for improving the yield and persistence of smokes generated from diesel fuel.

2. The quality of smoke that can be produced from diesel fuel is comparable to fog oil.

3. Excessive superheating has a deleterious effect on the quality of smoke unless it is counteracted by air entrainment in the discharge nozzle.

4. The aspiration of air in a venturi eductor nozzle to mix with the diesel fuel vapors in the diverging section of the nozzle produced a smoke essentially comparable to that produced from fog oil.

5. An open tube discharge nozzle gives a more dense smoke than a venturi nozzle and a less dense smoke than a venturi eductor nozzle with entrainment of air.

6. Diesel fuel premixed with water prior to vaporization improves the quality of smoke.

7. Increasing the rate of discharge of fog oil reduces the overall quality of smoke obtained.

8. The combined effect of diesel fuel premixed with water prior to vaporization with subsequent entrainment of air at the discharge nozzle is only slightly better than that of entrained air with the diesel fuel vapors at the discharge nozzle.

9. The addition of salts in solution either by premixing with diesel fuel prior to vaporization or by postmixing with diesel fuel vapors at the discharge nozzle does not improve the quality of smoke obtained.

10. The addition of salt solutions by premixing with diesel fuel prior to vaporization produces a better quality smoke than postmixing of salt solution with diesel fuel vapors at the discharge nozzle. The use of a salt solution to enhance the quality of smoke produced from diesel fuel may create design and operating problems in the smoke generator since the salts precipitate from the vapors and coat the vaporizer tubing and discharge nozzle.

11. The addition of water by premixing with diesel fuel prior to vaporization produces a better quality smoke than postmixing with diesel fuel vapors at the discharge nozzle.

12. The addition of talc to the diesel fuel vapors at the discharge nozzle enhances both the yield and persistence of smoke.

13. Smokes produced from diesel fuel with entrained air, diesel fuel with nitrogen, diesel fuel mixed with talc at the discharge nozzle and fog oil did not scatter measurable light at 90° to the light beam.

14. A change in the operating procedure--the use of the wind tunnel blower--appears to improve the results obtained by the light measuring system installed in the exhaust stack.

15. Experimental data obtained by the methodology in this research program are insufficient to quantify with certainty all the effects of the variables or additives on the quality of smoke (yield and persistence) produced from diesel fuel.

7. RECOMMENDATIONS

Since the "leap-frog" approach has been used in this experimental research program, a systematic evaluation of the variables has not been possible. Further, the effects of adding candidate materials such as zinc chloride, titanium dioxide, alumina, carbon, gelling agents and encapsulating agents which could enhance the quality of smoke produced from diesel fuel have not been explored in the experimental facility at the University of Oklahoma. It is, therefore, recommended that the experimental research program be extended with appropriate funding to include at least the following:

1. Continued evaluation of the effect of superheat on the quality of smoke produced from fog oil and diesel fuel.

2. Evaluation of glare produced by smoke screens by measuring the scattered light in the smoke screen with the light transmission measuring system.

3. Evaluation of the effect of adding solid particles such as zinc chloride, titanium dioxide, alumina and carbon on the quality of smoke produced from diesel fuel.

4. Evaluation of the effect of adding gelling agents to diesel fuel on the quality of smoke obtained.

5. Evaluation of the effect of adding encapsulating agents to diesel fuel on the smoke quality.

APPENDIX

PROPERTIES OF DIESEL FUEL AND FOG OIL

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Table 1. Significant Physical and Chemical Properties of the Three Primary Current US Smoke-Producing Liquids*

LIQUID PHYSICAL PROPERTY	FOG OIL (SGF-2)	DIESEL FUEL (DF-2)	POLYETHYLENE GLYCOL 200 (PEG-200)
Density @ 60°F, gm/cm^3	0.920	0.850	1.127
Density @ 60°F, deg. API	22.4	35.5	NA
Mean Vapor Pressure @ 32°F	1.6×10^{-5}	2.5×10^{-2}	2.9×10^{-6}
Viscosity, (centistokes)			
@ 32°F	300.0	8.3	230.0
@ 60°F	80.0	5.0	80.0
@ 100°F	22.5	2.9	24.0
@ 210°F	3.5	1.2	4.3
Characterization Factor, K	11.4	11.7	NA
Mean Average Boiling Point, °F	700.0	510.0	590.0
End Point Distillation Temp, °F	870.0	650.0	770.0
Mean Specific Heat of Liquid, from 70°F to Mean B. Pt., BTU/lb °F	0.58	0.55	0.72
Heat of Vaporization @ Mean B. Pt., BTU/lb	92.0	104.0	160.0
Mean Molecular Weight, lb/lb-mole	300.0	205.0	201.0
Heat Required to Vaporize, BTU/gal(**)	3,565.0	2,515.0	5,235.0

*Data Sheet from Material Distributed at Second Diesel Fuel Chemical Conference, Aberdeen Proving Ground, MD, Jan. 1986.

**From a liquid initially at 70°F to a vapor having a superheat at 29°F. (The comparable value for water is 9340 BTU/gal.)

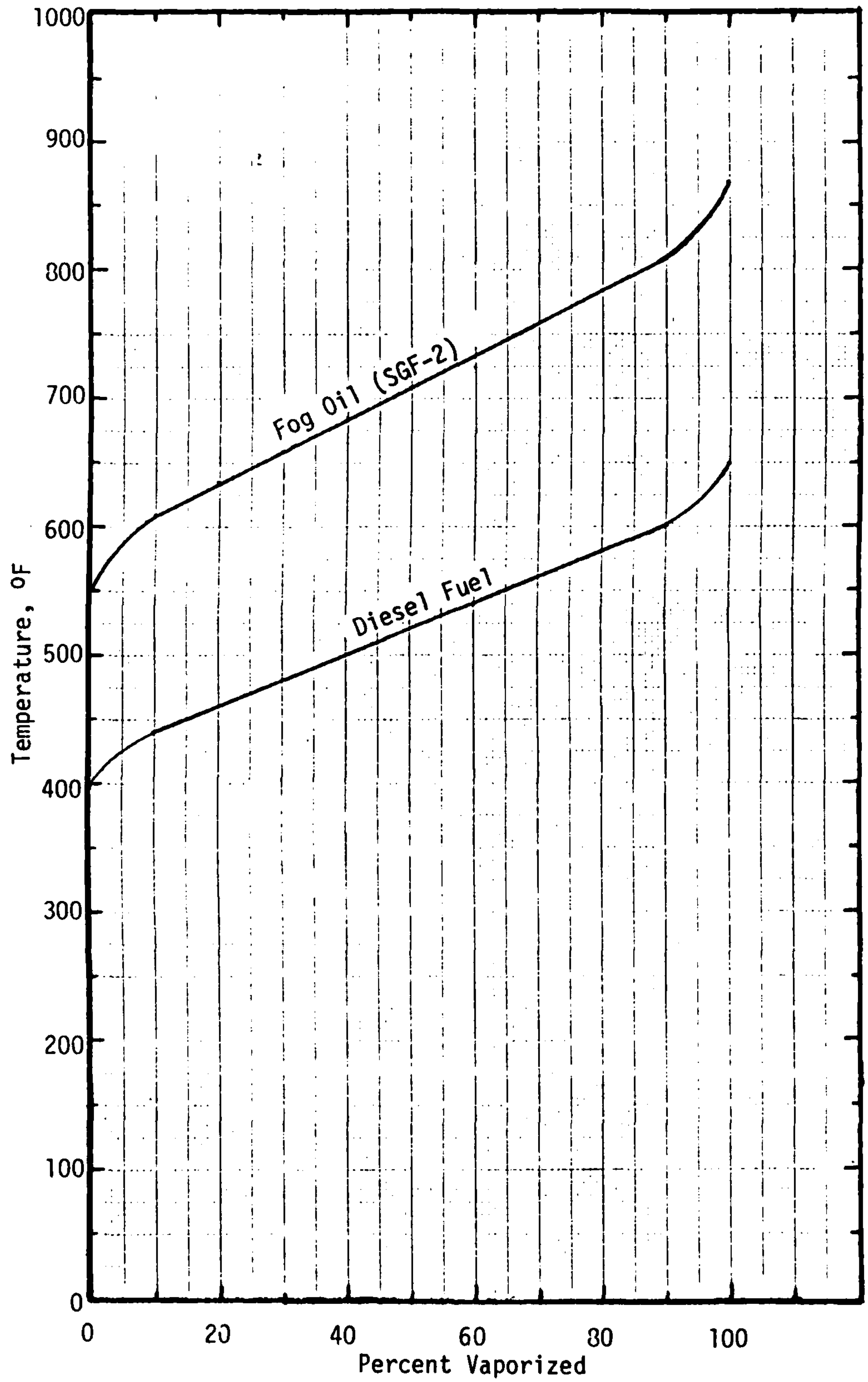

Figure. Distillation Curves for Diesel Fuel and Fog Oil (SGF-2) (Received from Dr. G. O. Rubel)

Table 2. Foil Oil SGF-2
Fractional Distillation Data*

$t^{o}F$	Fraction of Original Volume Evaporated
675	0.12
700	0.35
725	0.52
750	0.68
775	0.79
800	0.87
900	0.96
925	0.96

*Material originally supplied by J. R. Brock, University of Texas, Austin, TX, received from Glenn Rubel

OAK RIDGE NATIONAL LABORATORY

OPERATED BY MARTIN MARIETTA ENERGY SYSTEMS, INC.

POST OFFICE BOX X
OAK RIDGE, TENNESSEE 37831

October 31, 1985

Dr. C. M. Sliepcevich
Universityof Oklahoma
1215 Westheimer Drive, Bldg. 802
Norman, Oklahoma 73069

Dear Dr. Sliepcevich:

Attached is a copy of the specifications and test results for the D-2 diesel fuel which was shipped to you as part of the Army's diesel fuel smoke persistency studies. You should have received a copy directly from Phillips, but I wanted to make sure we all had the same information. If you have any questions, don't hesitate to call me at 615-574-4869.

Sincerely,

Roger A. Jenkins

Roger A. Jenkins, Ph.D.
Organic Chemistry Section
Analytical Chemistry Division

RAJ:djg

Attachment

cc: R. W. Holmberg

Laboratory Test Report

PHILLIPS CHEMICAL COMPANY
A SUBSIDIARY OF PHILLIPS PETROLEUM COMPANY

BARTLESVILLE, OKLAHOMA 74004

DATE OF SHIPMENT 10-10-85
CUSTOMER ORDER NO. 37X-52339V
INV. OR REQN. NO. 54801M

D-2 DIESEL CONTROL FUEL

LOT G-075

	Results	EPA Specification*	Test Method
Cetane Number	46.2	42 - 50	D 613
Distillation Range, °F			
IBP	375	340 - 400	D 86
5%	415		
10	431	400 - 460	
20	451		
30	469		
40	487		
50	505	470 - 540	
60	523		
70	543		
80	567		
90	598	550 - 610	
95	628		
DP	648		
EP	653	580 - 660	
Gravity, °API	35.2	33 - 37	D 287
Total Sulfur, WT%	0.35	0.2 - 0.5	D 3120
Aromatics (FIA), Vol%	32.1	27 Min.	D 1319
Kenematic Viscosity, cs	2.52	2.0 - 3.2	D 445
Flash Point (PM, °f)	162	130° Min.	D 93
Particulate Matter, mg/l	2.1	-	D 2276
Cloud Point, °F	+12		
Pour Point, °F	0		
Elemental Analysis, WT%			
C	86.12		
H	12.92		
N	0.08		
O	0.06		
C/H	6.66		

30.0 ptb of Du Pont FOA #11 antioxidant enhances the stability of this fuel.

*Diesel Fuel as described in Chapter One-Environmental Protection Agency, Subsection 86.113-78, of the Code of Federal REgulations.

FORM 8826-N 1-81

END

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